LCA of New Zealand Mussels & Oysters

On behalf of Aquaculture New Zealand and the Ministry for Primary Industries

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Executive Summary

Changing what we eat is one of the most effective ways to lower our carbon footprint

Food production has a significant carbon footprint. Farmed shellfish have the potential to be a low-impact part of our diet. They are nutritionally rich, high in protein, and can be grown without supplementary feeds – taking what they need to develop directly from the water column.

Understanding the sustainability of a food source requires comprehensive data

Aquaculture New Zealand (Aquaculture NZ) and the Ministry for Primary Industries (MPI) engaged thinkstep-anz to carry out a Life Cycle Assessment (LCA) of farmed New Zealand Greenshell Mussels and farmed Pacific Oysters.

The goals of the LCA were to:

- quantify the environmental performance of shellfish across several different indicators.
- identify hotspots where improvements will have the greatest impact.
- compare the carbon footprint of mussels and oysters with other forms of edible protein.

This study follows international standards ISO 14044 and ISO 14067 and covers the full life cycle of shellfish from farming to final consumption.

New Zealand-farmed mussels and oysters have among the lowest carbon footprint of all animal proteins

Figure 1 shows that New Zealand-farmed mussels and oysters have a lower carbon footprint per 100 g of protein than all other animal products studied. Mussels have a carbon footprint comparable to tofu – an important vegetable protein.

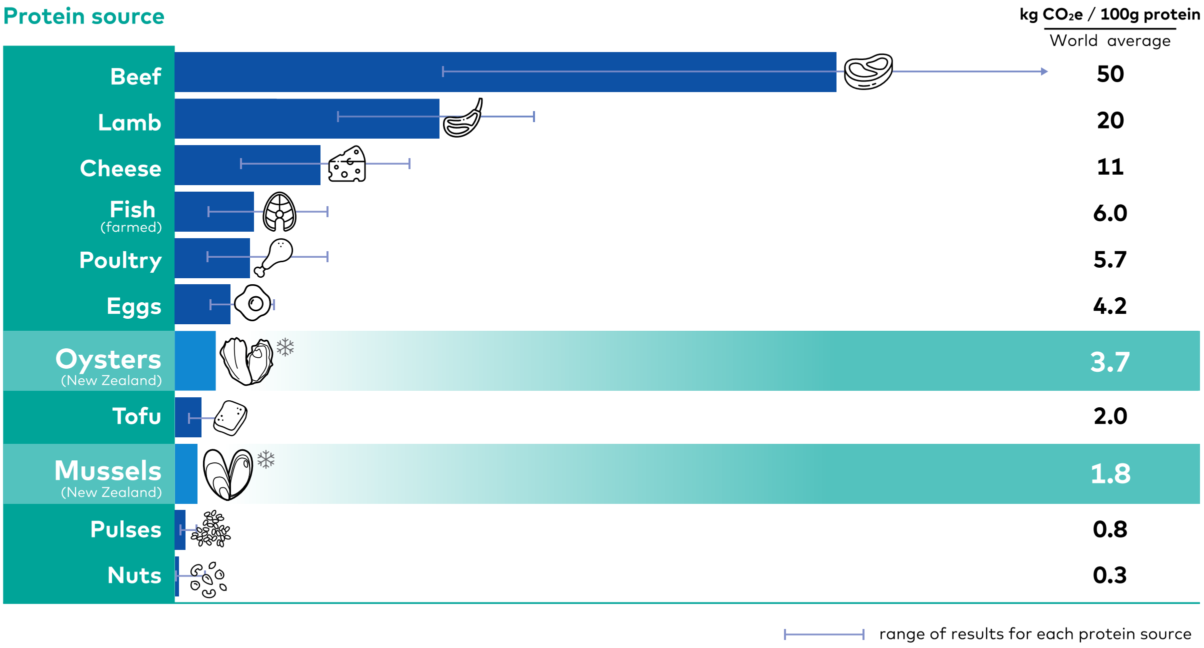

Figure 1: Carbon footprints of different dietary proteins on the global market – farming to retail only *

Recommendations for reducing the carbon footprints of these products

This study finds that farmed shellfish is a protein source with a low carbon footprint. To help keep New Zealand shellfish on the menu as a low-carbon food source, we recommend the mussel and oyster industries consider the following changes in future:

- Use vehicles (barges and trucks) more efficiently and convert them to run on low-carbon renewable energy sources, such as electricity, biodiesel or hydrogen.
- Switch from burning fossil fuels for thermal energy in processing facilities to low-carbon renewable energy sources, such as biomass or electric boilers.
- Further analyse plastic use in the industry, especially for ocean-contact plastics.
- Seek ways to reuse production waste, particularly organic waste (circular economy).
- Reduce the amount of packaging used and/or use reusable packaging.
- Encourage air cargo operators to explore low-carbon fuel alternatives.
- Increase the share of the domestic and regional live product markets, as air freighting fresh product over long distances has a large carbon footprint.
- Expand the frozen export market, as exporting frozen product in cargo ships has a low carbon footprint, even over long distances.

Conclusions

New Zealand farmed mussels have a lower carbon footprint than all other forms of animal protein considered in this study, including protein from land animals, farmed fish, and farmed crustaceans. In addition, the carbon footprint of producing frozen half shell mussels is comparable to tofu – a major global source of plant-based protein.

New Zealand farmed oysters have a carbon footprint at the lowest end of the spectrum of animal proteins, comparable to protein from eggs and poultry meat. Frozen half shell oysters have the lowest carbon footprint of all oyster products considered.

The carbon footprint of distribution is relatively insignificant for frozen sea-freighted shellfish (7%-11% of the whole-of-life carbon footprint), but highly relevant for air-freighted shellfish (>70% of the whole-of-life carbon footprint).

Live shellfish which are exported overseas from New Zealand have approximately seven times the impact of frozen shellfish (on average) over their full life cycle. This is due to the significant carbon footprint of air freight per kilometre and the significant distance between New Zealand and most of its major live export markets. Any strategy which seeks to increase the value per kilogram of shellfish by increasing the market share of exported live products is likely to increase the overall carbon footprint of New Zealand's mussel and oyster industries. Live sales should ideally focus on the domestic market and local international markets, such as Australia and the Pacific Islands, or look at ways to significantly reduce the carbon emissions of air freight.

* The carbon footprints of other nutritional proteins in Figure 1 come from global production data from Poore and Nemecek (2018). All products are shown using a system boundary that spans from farming to retail, for internal consistency. The results for mussels and oysters in Figure 1 are for frozen half shell products, as this is the product format with the largest market share. The bars in Figure 1 are used to show the tenth and ninetieth percentiles (the range within which 80% of producers will fall). These bars indicate the range of results for a particular protein source, due to different production methods, technologies, and locations.

Technical Summary

Changing what we eat is one of the most effective ways to lower our carbon footprint

As action on climate change becomes increasingly urgent, individuals, organisations, and countries are increasingly looking for ways to reduce their carbon footprints. A person's diet is a significant part of their individual carbon footprint, and food production and consumption make up a significant portion of the carbon footprint of nation states. In New Zealand, agriculture on land makes up approximately half of all national greenhouse gas emissions.

Farmed shellfish have the potential to be a low-impact part of our diet. They are nutritionally rich, high in protein, and can be grown without supplementary feeds – taking what they need to develop directly from the water column through filter-feeding.

Understanding the sustainability of a food source requires comprehensive data

Aquaculture New Zealand (Aquaculture NZ) and the Ministry for Primary Industries (MPI) engaged thinkstep-anz to carry out a Life Cycle Assessment (LCA) of farmed New Zealand Greenshell Mussels (*Perna canaliculus*) and farmed Pacific Oysters (*Crassostrea gigas / Magallana gigas*).

The goals of the LCA were to:

- quantify the environmental performance of shellfish across several different indicators.
- identify hotspots where improvements will have the greatest impact.
- compare the carbon footprint of mussels and oysters with other forms of edible protein.

This study follows international standards ISO 14044 and ISO 14067 and covers the full life cycle of shellfish, including shellfish farming, harvesting, processing (which for mussels includes heat treatment), packaging, chilled distribution, cooking (for mussels only), consumption, and disposing of used shells and packaging. The environmental impact categories included in this study are: Global Warming Potential (also known as the carbon footprint), Ozone Depletion Potential, Acidification Potential, Eutrophication Potential, and Photochemical Ozone Formation Potential (also known as summer smog).

The functional unit chosen for this study is one kilogram of edible shellfish meat of New Zealand-produced fresh mussels and oysters, covering their entire life cycle, including packaging. To compare these food systems with other forms of nutritional protein, the results have been converted to impacts per 100 grams of protein.

The carbon footprint of New Zealand mussels and oysters

The whole-of-life carbon footprint of mussels and oysters depends on the type of product. Different products use different packaging and involve differing loss rates along supply chains. For a kilogram of shellfish meat, the whole-of-life carbon footprint of frozen half shell mussels is 2.0 kilograms of CO_2-equivalent (kg CO_2e), while frozen half-shell oysters have a footprint of 5.1 kg CO_2e per kg shellfish meat.

One significant reason for this difference is that mussels have a higher meat-to-shell ratio than oysters, which has flow-on effects through the supply chain (for example, more packaging is also needed). Live and potted mussel and oyster products have significantly higher carbon footprints, largely due to higher packaging requirements (as can be seen in Figure 1-1). For both frozen mussels and frozen oysters, the farming stage is the most significant in the life cycle. This is largely due to the diesel used in vehicles (trucks and barges) and the carbon dioxide released naturally when shellfish form their shells (see section 3.4 for more information). Processing is also a significant life cycle stage (particularly for live shellfish and potted meat), due to the impacts of packaging (for both mussels and oysters) and the energy needed to heat-treat mussels during processing.

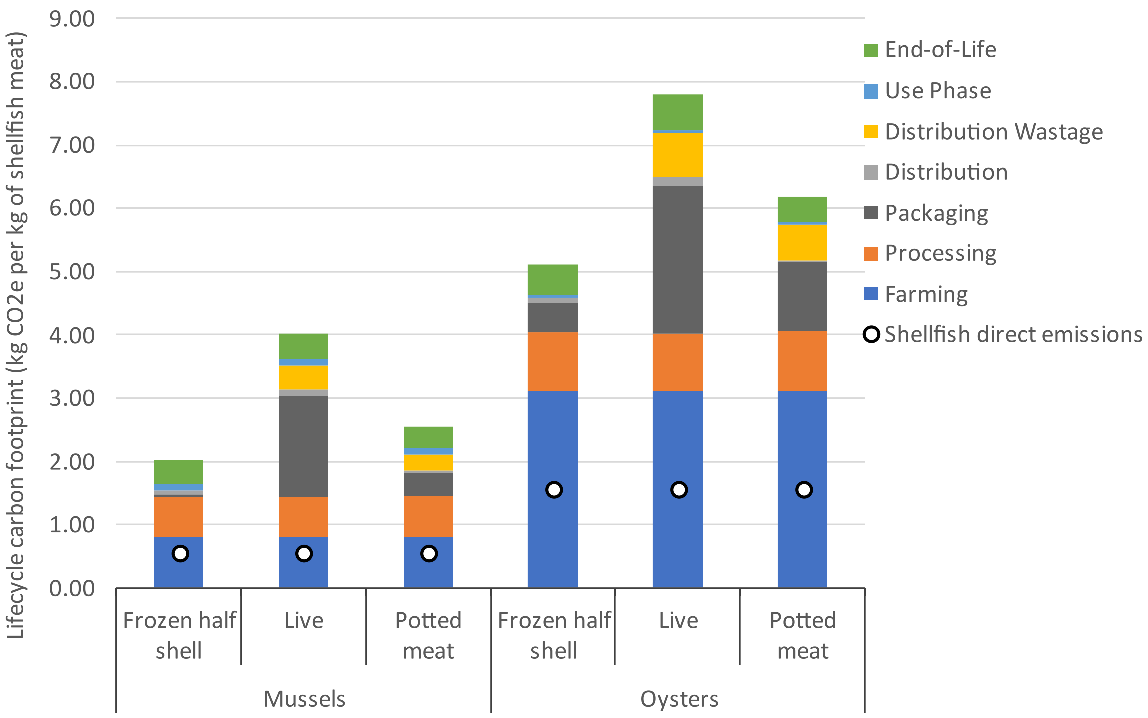

Figure 1-1: Carbon footprint of mussel and oyster products per kilogram of shellfish flesh, local distribution

Key modelling decisions

Modelling decisions and assumptions are necessary in any Life Cycle Assessment. This report documents the decisions and assumptions made when we collected the data and modelled each product's life cycle. The choices made in this report which have a notable effect on results are:

- Live and potted products have distribution and retailing waste of 9.3%, while frozen products have no waste associated with these stages. See 3.2.7 and 3.3.7 for details.
- Emissions associated with producing capital goods (for example, barges used in shellfish farming) are excluded. This is a common exclusion in Life Cycle Assessment.
- Shellfish release 0.29 kg CO_2 per kilogram of shell formed, due to the reaction which takes place to create calcium carbonate. Most other shellfish studies do not include this interaction with the environment. More information can be found in section 3.4.

Export versus domestic sales

As Figure 1-2 shows, the carbon footprints of frozen mussels and oysters do not significantly increase when they are exported overseas as container ships are a very efficient form of freight. Exported live mussels and oysters have a significantly higher carbon footprint than when they are sold domestically, due to the impacts associated with air freight. For more information on these results, please refer to section 4.4.

For all products, the distribution distance is calculated as the weighted average distance that exported products are transported. For live mussels and live oysters, this is 9,500 km and 9,800 km respectively – approximately the distance between New Zealand and China. For frozen half shell mussels, this is 11,700 km – approximately the distance to Los Angeles. For frozen half shell oysters, this is 5,400 km – approximately the distance to Perth.

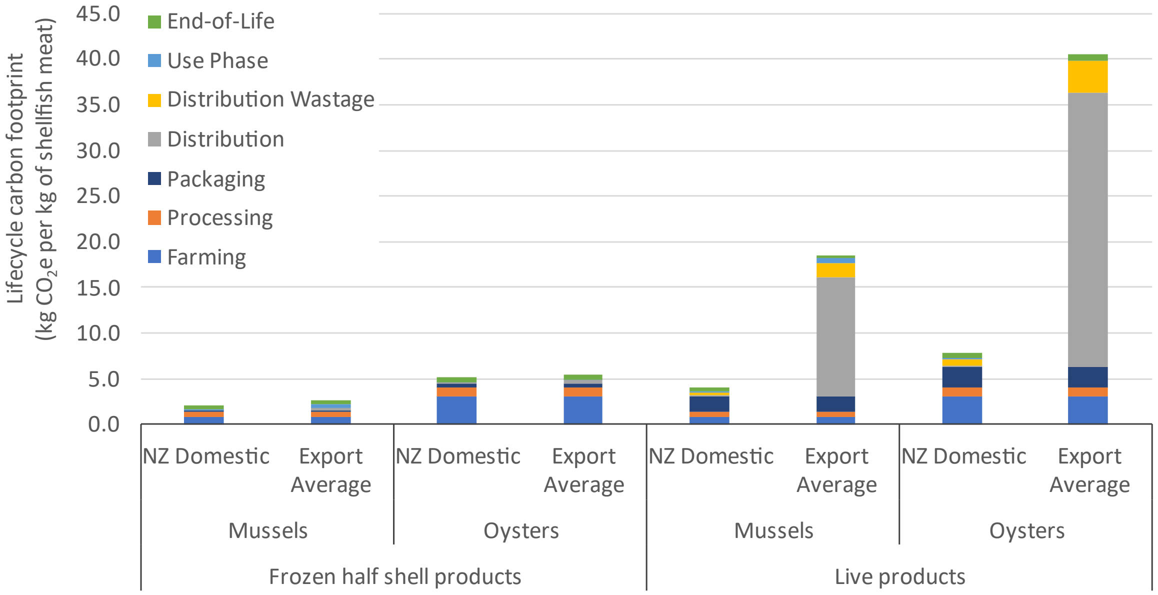

Figure 1-2: Carbon footprint of mussel and oyster live and frozen products, export vs domestic market

New Zealand-farmed mussels and oysters have among the lowest carbon footprint of all animal proteins

Figure 1-3 compares the carbon footprint of New Zealand-farmed mussel and oyster products to other high-protein food sources (per 100 g of protein) in the study by Poore and Nemecek (2018). Mussels and oysters have a lower carbon footprint per 100 g of protein than most other animal products studied, with frozen and potted mussels comparable to tofu. For all products, this comparison only considers a domestic ‘cradle-to-retail’ system boundary (i.e., farming, processing, distribution, and distribution loss if applicable), as this is the boundary applied by Poore and Nemecek. As seen in Figure 1-2, distribution impacts can be significant for live shellfish, so care must be taken with these results as they do not apply to live shellfish exported overseas. Bars are used to show the tenth and ninetieth percentiles (the range within which 80% of producers will fall). These bars indicate the range of results for a particular protein source, due to different production methods, technologies, and locations.

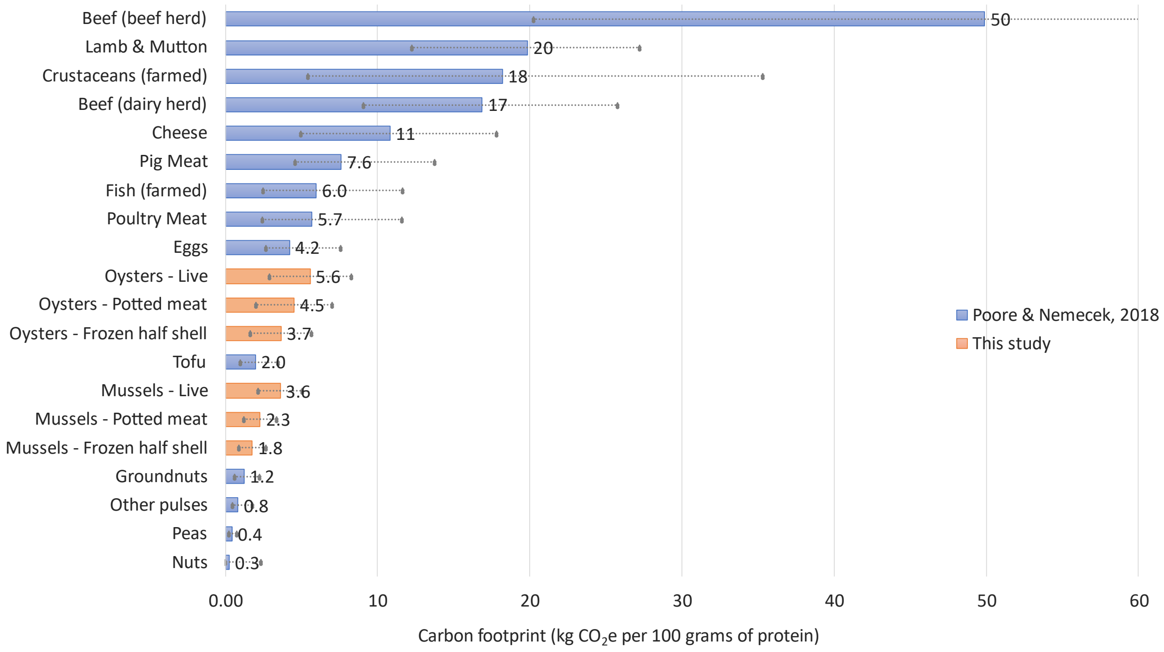

Figure 1-3: ‘Cradle-to-retail’ carbon footprint of high protein food sources (domestic market) (Poore & Nemecek, 2018).[1]

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[1] The x-axis is truncated as the upper value for “Beef (beef herd)” is 105 kg CO_2eq per 100 grams of protein and showing this would compress the rest of the graph.

Other environmental indicators

Four other environmental indicators were considered in this study alongside carbon footprint (GWP). These were Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP) and Photochemical Ozone Formation Potential (POFP). For the most part, these indicators had the same hotspots as the carbon footprint (fuel use during farming and processing). The major exception to this is ODP, where the impacts came almost entirely from refrigeration, due to some companies using older refrigerants. The uptake of nitrogen compounds during shellfish filter feeding was considered but not modelled due to significant uncertainties.

Recommendations for reducing the carbon footprints of these products

This study finds that farmed shellfish is a protein source with a low carbon footprint. The aquaculture industry can make further life cycle improvements to combat climate change. To help keep New Zealand shellfish on the menu as a low-carbon food source, we recommend the mussel and oyster industries consider:

- Reducing the amount of packaging used and/or using reusable packaging (while ensuring that systems are in place for the packaging to be used again).
- Using vehicles (barges and trucks) which run on low-carbon renewable energy sources, such as electricity, biodiesel or hydrogen. Using vehicles more efficiently to reduce fuel is also a relatively easy way to reduce environmental impacts.
- Switching from burning fossil fuels for thermal energy in processing facilities to low-carbon renewable energy sources, such as biomass or electric boilers.
- Further analysing plastic used in the industry, especially for materials that are in contact with the ocean and are likely to release microplastics as they break down.
- Reducing wastage of shellfish across the supply chain.
- Encouraging air cargo operators to explore low-carbon fuel alternatives as transporting live shellfish by air significantly increases their carbon footprint.
- Increasing the share of the domestic and regional live product markets, as exporting live product over large distances causes a large carbon footprint.
- Expanding the frozen export market, as exporting frozen product in cargo ships has a low environmental impact.

More recommendations can be found in section 5.6.3.

Conclusions

New Zealand farmed mussels have a lower carbon footprint than all other forms of animal protein considered in this study, including protein from mammals, farmed fish, and farmed crustaceans. In addition, the carbon footprint of producing frozen half shell mussels and potted mussel meat is comparable to tofu – a major global source of plant-based protein.

New Zealand farmed oysters have a carbon footprint at the lowest end of the spectrum of animal proteins, comparable to protein from eggs and poultry meat. Frozen half shell oysters have the lowest carbon footprint of all oyster products considered.

The carbon footprint of distribution is relatively insignificant for frozen sea-freighted shellfish (7%-11% of the whole-of-life carbon footprint), but highly relevant for air-freighted shellfish (>70% of the whole-of-life carbon footprint).

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Acknowledgements

This report and the underlying Life Cycle Assessments have been funded by the Ministry for Primary Industries (MPI) and Aquaculture New Zealand (AQNZ).

We would also like to acknowledge the contributions from the organisations listed below:

- Aroma Aquaculture
- Biomarine Oysters
- Clearwater Mussels
- Clevedon Coast Oysters
- Gold Ridge Marine Farms
- Gulf Mussel Farms
- Kono Seafoods
- MacLab NZ
- Moana New Zealand
- National Institute of Water and Atmospheric Research (NIWA)
- North Island Mussels Ltd (NIML)
- Nelson Ranger Fishing Co (NRFC)
- OP Columbia
- Sanford
- Taniwha Oysters
- Westpac Mussels

These organisations either provided data for the Life Cycle Assessment or feedback on earlier versions of this report. Any remaining errors or omissions are those of the authors.

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Glossary of Terms

Life cycle

A view of a product system as "consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal" (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land and water.

Life Cycle Assessment (LCA)

"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040:2006, section 3.2)

Life Cycle Inventory (LCI)

"Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (ISO 14040:2006, section 3.3)

Life Cycle Impact Assessment (LCIA)

"Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (ISO 14040:2006, section 3.4)

Life cycle interpretation

"Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations" (ISO 14040:2006, section 3.5)

Environmental Product Declaration (EPD)

"Independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of products."

Product Category Rule (PCR)

"Defines the rules and requirements for EPDs of a certain product category."

Functional / Declared unit

"Quantified performance of a product system for use as a reference unit." (ISO 14040:2006, section 3.20)

Functional unit = LCA/EPD covers entire life cycle "cradle to grave".

Declared unit = LCA/EPD is not based on a full "cradle to grave" LCA, common in construction product EPDs.

Allocation

"Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" (ISO 14040:2006, section 3.17)

Foreground system

"Those processes of the system that are specific to it … and/or directly affected by decisions analysed in the study." (JRC, 2010, 97) This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

Background system

“Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process … and/or those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good….” (JRC, 2010, 97-98) As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

Closed-loop and open-loop allocation of recycled material

“An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.”

“A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.”

(ISO 14044:2006, section 4.3.4.3.3)

Critical Review

“Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment” (ISO 14044:2006, section 3.45).

Spat

Very young shellfish (including mussels and oysters)

Cradle-to-grave

A full Life Cycle Assessment which considers all impacts “throughout a product’s life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal” (ISO 14044:2006, Introduction)

Cradle-to-gate

An assessment which covers the creation of a product up to the factory “gate”, before it is distributed to the consumer.

Cradle-to-retail

This term has been coined in this study to describe the scope of the comparison to the Poore and Nemecek study (2018). It covers the creation of a product up to the retailer, just before the product is purchased by the eventual consumer.

Global Warming Potential (GWP)

A measure of greenhouse gas emissions, such as carbon dioxide and methane.

Acidification Potential (AP)

A measure of emissions that increase the acidity of the environment.

Eutrophication Potential (EP)

A measure of the excessive addition of nutrients (such as nitrogen and phosphorus) to a water system resulting in increased aquatic plant and algal growth.

Photochemical Oxidant Formation Potential (POFP)

A measure of emissions that contribute to air pollution in the form of smog.

Coefficient of variation

A measure of the relative variability of a population, calculated by dividing the standard deviation by the mean of that population.

Food loss

“is the decrease in the quantity or quality of food resulting from decisions and actions by food suppliers in the chain, excluding retail, food service providers and consumers.” (FAO, 2019)

Food waste

“is the decrease in the quantity or quality of food resulting from decisions and actions by retailers, food services and consumers.” (FAO, 2019)

List of Acronyms

ADP	Abiotic Depletion Potential
AP	Acidification Potential
CML	Centre of Environmental Science at Leiden
CNG	Compressed Natural Gas
COV	Coefficient of Variation
DQI	Data Quality Indicator
ELCD	European Life Cycle Database
EoL	End-of-Life
EP	Eutrophication Potential
EPD	Environmental Product Declaration
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GW	Green Weight (live weight)
GWP	Global Warming Potential
GWPA	Global warming potential (aviation)
GWPB	Global warming potential (biogenic)
GWPF	Global warming potential (fossil)
GWPLULUC	Global warming potential (land use and land use change)
HDPE	High Density Polyethylene
ILCD	International Cycle Data System
ISO	International Organization for Standardization
IQF	Individually Quick Frozen
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LPG	Liquid Petroleum Gas
NMVOC	Non-Methane Volatile Organic Compound
ODP	Ozone Depletion Potential
PEFCR	Product Environmental Footprint Category Rules
PET	Polyethylene terephthalate
POFP	Photochemical Ozone Formation Potential
SARF	Scottish Aquaculture Research Forum
SFP	Smog Formation Potential
VOC	Volatile Organic Compound

1. Goal of the Study

This study was commissioned by Aquaculture New Zealand (Aquaculture NZ) and the New Zealand Ministry for Primary Industries (MPI).

The study aims to:

1. Quantify the environmental performance of farmed mussels and farmed oysters produced in New Zealand.
2. Identify hotspots for potential future process improvements across the mussel/oyster life cycle.
3. Compare the environmental footprint of mussels and oysters with other forms of edible protein to help put the results into context.

The primary stakeholders for this study are:

- Mussel and oyster farmers and processors
- Central and local government
- Community interest groups
- Environmental groups
- New Zealand seafood industry companies
- Shellfish consumers

Life Cycle Assessment (LCA) has been used to evaluate potential environmental impacts of farmed mussels and oysters. LCA is an established method based on international standards — ISO 14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b) — to objectively and scientifically assess the resource requirements of a product, its production of waste and other emissions, and its potential impacts on the environment.

This LCA report can be used by Aquaculture NZ, MPI, and the wider New Zealand mussel and oyster industries for both business-to-business and business-to-customer communication. This report includes a comparison of the environmental footprint of mussels and oysters to other forms of protein to help put the results into context. As such, this report has undergone a critical review by a panel of three experts to meet the requirements of ISO 14044.

2. Scope of the Study

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to:

- The identification of specific product systems to be assessed.
- The product function(s).
- Functional unit and reference flows.
- The system boundary.
- Allocation procedures.
- Cut-off criteria of the study.

2.1. Product Systems

The studied products within this report are mussels (New Zealand Greenshell Mussels, *Perna canaliculus*) and oysters (Pacific Oysters, *Crassostrea gigas/Magallana gigas*), produced around New Zealand and consumed both in New Zealand and internationally.

2.2. Product Function(s) and Functional Unit

The functional unit is the consumption of 1 kilogram (kg) of meat of New Zealand-produced mussels and oysters over their entire life cycle. Mussel flesh is cooked during processing, while oysters are consumed raw. The shellfish and packaging masses per 1 kg of flesh can be seen in Table 2-1. The full packaging material breakdown can be seen in section 3.2.6 for mussels and section 3.3.6 for oysters.

Table 2-1: Product and packaging masses per kilogram of flesh

Product	Shellfish product mass (kg) (including shell)	Packaging mass (kg)
Frozen half shell mussels	1.53	0.14
Live mussels	2.05	0.53
Potted mussels	1.00	0.14
Frozen half shell oysters	2.90	0.25
Live oysters	4.81	0.95
Potted oysters	1.00	0.33

Nutritional information of New Zealand Greenshell Mussels and Pacific Oysters are summarised in Table 2-2 below. It has been assumed that frozen products have the same nutritional information as fresh products.

Table 2-2: Nutritional information of raw New Zealand Greenshell Mussels and Pacific Oysters (New Zealand Institute for Plant and Food Research, 2018)

Nutrition per 100g fresh, raw flesh	Greenshell Mussel	Pacific Oyster
Energy (kJ)	311	392
Protein (g)	10.7	13.6
Fat, total (g)	1.8	3.8
Carbohydrate (g)	3.7	1.2
Sugars (g)	0.7	0.2
Water (g)	81.3	78.3
Sodium (mg)	470	350
Calcium (mg)	91	44
Iron (mg)	4.1	9.4
Zinc (mg)	1.6	10
Selenium (µg)	70	140
Vitamin B12 (µg)	6	17

Aside from providing protein, mussels and oysters are also high in micronutrients, like vitamins and minerals. Examples of micronutrients found in high levels in these shellfish include zinc, magnesium, calcium, selenium, and vitamin B12. Both mussels and oysters also contain long chain omega-3 fatty acids which can reduce inflammation (Miller, et al., 2014).

As the outputs of both the mussel/oyster farms and processors include the masses of the shells (in kg), conversions were required to calculate the fraction of raw flesh relative to the total product mass. Table 2-3 shows the shell mass as a percentage of the total mussel/oyster mass and how this is used to calculate the shell mass as a percentage of half shell mussels/oysters. The flesh mass percentage of half shells is then used to calculate the protein content of 1 kilogram of half shell mussels/oysters. Oyster producers record their output in dozens of oysters and, according to industry, on average, a dozen weighs 0.8 kg. This means that a dozen oysters contain 0.1664 kg of meat, resulting in 6.01 dozen oysters per kilogram of meat.

Table 2-3: Shell masses of raw mussels and oysters

	Greenshell Mussel	Pacific Oyster
Shell mass % of live weight full shell	51.3% (Miller & Tian, 2017)	79.2% (Cochet, et al., 2015)
Shell mass % of half shell	34.5%	65.6%
Flesh mass % of half shell	65.5%	34.4%

2.2.1. Mussel and Oyster Products

Both mussels and oysters come in a range of products, including live, frozen, and chilled. The results in the main body of this report focus on the live and frozen half shell products for both mussels and oysters as these are the products which provide the majority of export revenue, as seen in Figure 2-1 (mussel products) and Figure 2-2 (oyster products).

Mussels can also be processed into powder or oil, the results for mussel powder are shown in Annex B. Due to reasons of confidentiality, this data will not be made public, and the results are shown to provide an indication of impacts. No data for mussel oil processing was able to be collected.

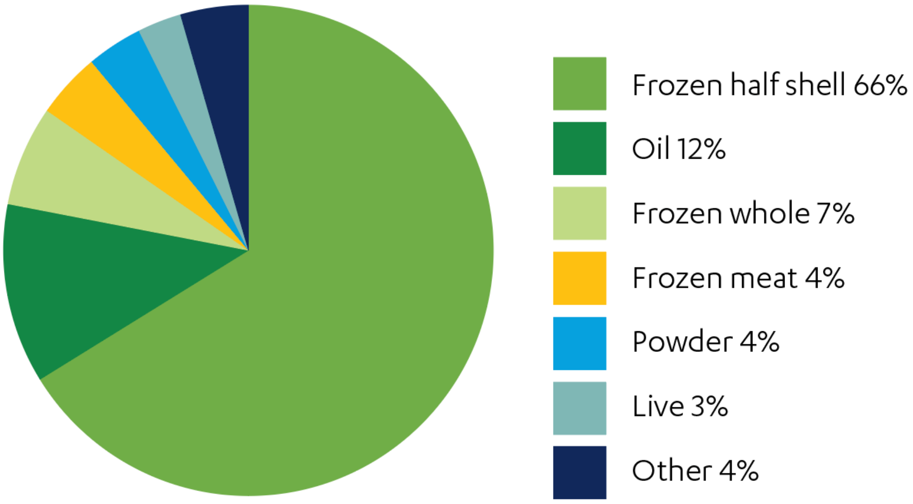

Figure 2-1: Mussel product exports by value in 2019 (Aquaculture New Zealand, 2020c)

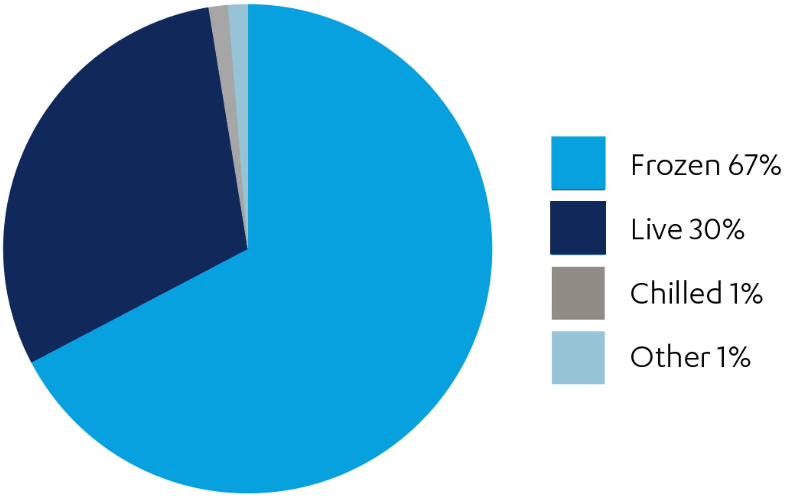

Figure 2-2: Oyster product exports by value in 2019 (Aquaculture New Zealand, 2020c)

2.3. System Boundary

2.3.1. General

This study includes all life cycle stages. It considers all relevant inputs and outputs to build a complete cradle-to-grave (i.e., all life cycle stages, from farming and processing to distribution, cooking, and disposal of the shellfish) model of mussels and oysters produced in New Zealand. The study is compliant with the ISO 14040, 14044 and 14067 international standards (ISO, 2006a) (ISO, 2006b) (ISO, 2018).

The main life cycle stages are as follows:

- Wild collection or hatchery production of juvenile (spat) mussels and oysters.
- Shellfish growth.
- Shellfish harvesting, shucking, processing and packaging.
    - Additional processing steps required for mussel oil and powder.
- Chilled distribution (both sea freight and air freight).
- Release of biogenic carbon and nutrients following consumption.
- Disposal of used shells and packaging.

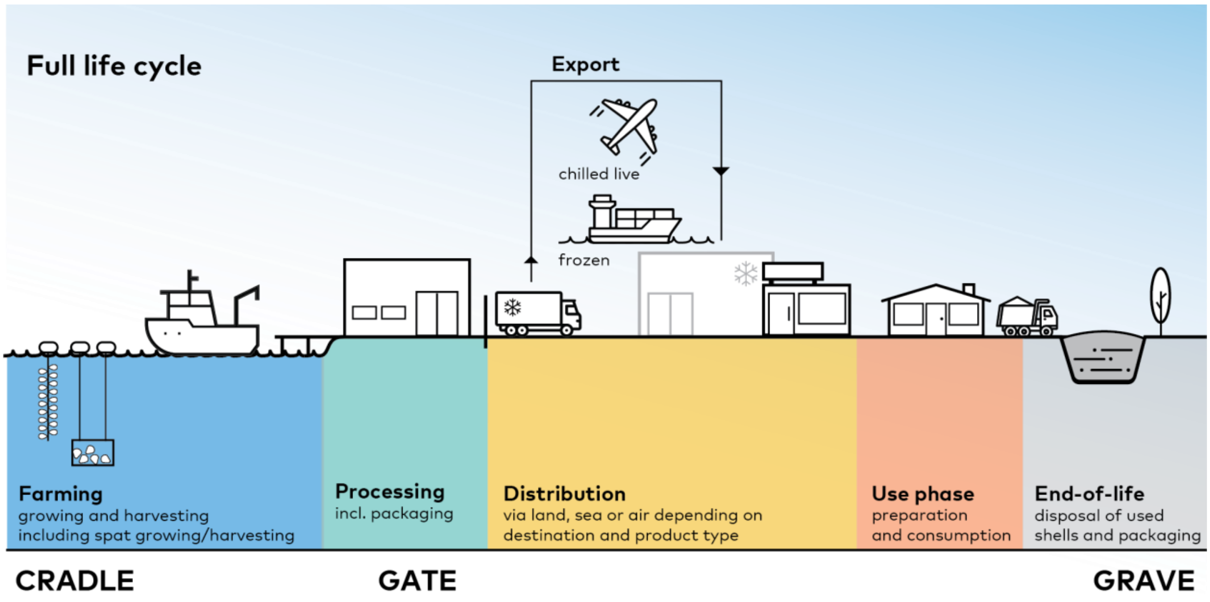

Figure 2-3: Life cycle of farmed shellfish

2.3.2. Technology and Geographical Coverage

Primary data for energy and material inputs and outputs is provided by the representative mussel and oyster farmers and processors located around New Zealand, taking a broad geographic and technological perspective.

Figure 2-4 shows the percentage of total New Zealand farming volume that each region contributes. For all regions that are shown as contributing more than 5% of the farming volume shown in Figure 2-4, data was collected from at least one farm operator based in that region.

Data has been collected from a range of farming methods for both mussels and oysters. Mussel and oyster processing methods are not deemed to be significantly different across New Zealand to warrant conscious diversification.

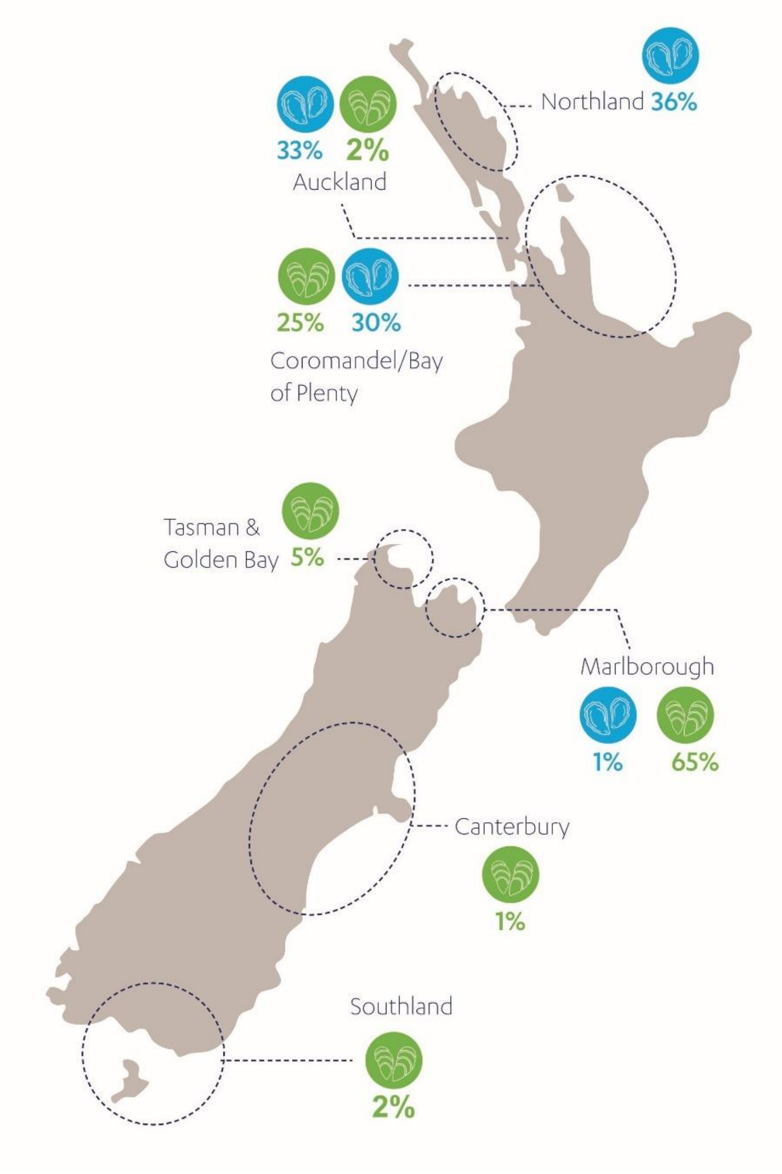

Figure 2-4: Geographical representation of all mussel and oyster farming in New Zealand, by production volume (mussels shown in green, oysters in blue) (Aquaculture New Zealand)

2.3.3. Time Coverage

Data used in the foreground/core system is for the 2019 calendar year, or for the latest full year the shellfish farmers have available.

Background system data are derived from the GaBi Life Cycle Inventory Database 2020 (see section 2.11 for more information) (Sphera, 2020). Most datasets have a reference year between 2016 and 2019. The specific reference year for the background datasets used in this study are given in section 3.5.

2.4. Biogenic Carbon in Product

Biogenic carbon is defined as carbon derived from materials of biological origin, excluding material embedded in geological formations (ISO, 2018). The shellfish products considered in this study, and in some cases the packaging contain biogenic carbon. The biogenic content of these materials per kilogram of product is show in Table 2-4.

The carbon in the shellfish themselves is split up into the carbon in the meat and the shell as they are formed through different mechanisms and are treated differently at the end-of-life of the product. Shellfish meat carbon is modelled as being a carbon removal during shellfish growth, and an equal magnitude emission during consumption. This assumes aerobic breakdown of the carbon in mussel meat. The exception to this is in the cradle-to-retail values shown in the executive summary and in sections 4.3.1 and 4.3.2 where the uptake of carbon in meat is not included. This is because in these values the corresponding release at consumption is not shown in cradle-to-retail values and including the uptake for these would contradict ISO 14067.

Carbon in packaging (cardboard) is modelled as sequestered carbon in the packaging phase and a release of carbon at the end-of-life phase.

Shell carbon is modelled as releasing carbon dioxide when it is formed as this is a by-product of the reaction to form calcium carbonate (see section 3.4 and Annex C for more information). It is assumed that the carbon in these shells remains in the shell after landfilling, due to landfills not being acidic or damp enough to break down the shell.

Table 2-4: Calculated biogenic carbon content per kilogram of shellfish (grams of carbon per kilogram of edible meat)

Product	Shellfish meat	Shellfish shell	Packaging
Live oysters	109	449	-
Frozen half shell oysters	109	224	84.1
Potted oysters	109	-	-
Live mussels	93.5	124	-
Frozen half shell mussels	93.5	62.1	66.9
Potted mussels	93.5	-	18.2

2.5. Allocation

Allocation in Life Cycle Assessment is the splitting of input and/or output flows of a process to the product system under study" (ISO, 2006b). This section provides guidance on how the environment impacts are divided when there are co-products involved and at the end-of-life of the materials involved in the life cycle.

2.5.1. Multi-output Allocation

Multi-output allocation concerns how environmental impacts are split when there are two or more co-products. For shellfish products with part of the shell removed (e.g. half shell oysters), the impacts are allocated to the meat alone and the shell being removed has no impacts allocated to it. For example, the processing impacts of a dozen half shell oysters are the same as the impacts of a dozen live oysters (excluding packaging), even though the half shell oysters weigh approximately 40% less than the live oysters. This was chosen due to the shells having no value and therefore no impacts can be allocated to them.

Within this study, there are no other cases of multi-output allocation in the foreground system. Mussel oil and mussel powder are not considered to be co-products as they are modelled as an additional processing step. Allocation of background data (energy and materials) taken from the GaBi 2020 databases is documented online (Sphera, 2020) and follows the requirements of ISO 14044, section 4.3.4.2.

2.5.2. Retailer to Customer Allocation

For the transportation of shellfish from retailer to consumer, the allocation factor has been determined following the PEFCR guidelines, where the volume of the product (and its packaging) is divided by 0.2 m^3 (which is a third of a trunk of 0.6 m^3). It has been estimated that 1 kilogram of shellfish and its packaging takes up approximately 0.01 m^3 of space, so the allocation factor of the product is 5 percent.

2.5.3. End-of-Life Allocation

End-of-Life allocation addresses the question of how to assign impacts from virgin production processes to material that is recycled and used in future product systems. This is important when a product system (e.g., the packaging) uses recycled content or is recycled at end-of-life. The approaches used in this study follow the requirements of ISO 14044, section 4.3.4.3.

The cut-off approach is used in this study, where the burdens associated with previous or subsequent life cycles are not considered, i.e., they are “cut-off”. Therefore, the scrap input to the production process is considered to be burden-free and, equally, no credit is received for scrap available for recycling at end-of-life. This approach rewards the use of recycled content but does not reward end-of-life recycling. The authors considered this approach to be the most appropriate for this study as the waste streams are of low economic value and low volume.

The system boundary includes the waste incineration and landfilling processes, following the polluter-pays-principle. In cases where materials are sent to landfills, they are linked to an inventory that accounts for waste composition, regional leakage rates, landfill gas capture as well as utilisation rates (flaring vs. power production). No credits for power or heat production from landfill gas are assigned.

2.6. Cut-off Criteria

Cut-off criteria refers to anything within the product system that is not included in the model. For this study, the exclusion of the production of capital goods such as barges, trucks and processing facilities is the only significant exclusion. Other materials and processes which have been excluded are:

- Packaging of the consumables used in farming and processing (e.g., ropes, socking, plastic bags).
- The commuting of employees to and from work.

The above exclusions were made as they were considered by the authors to be below the cut-off threshold of 1% of the mass, energy, and environmental significance to the studied systems. This follows the guidance General Program Instructions of the International EPD System (IEPDS, 2019). As summarised in section 2.3, the system boundary was defined based on relevance to the goal of the study. No other cut-off criteria have been defined for this assessment and all reported data have been incorporated and modelled using the best available LCI data. Where specific datasets are not available for a given input or process these have been modelled using proxy data.

The choice of proxy data is documented in section 3.5.

2.7. Selection of Environmental Impact Categories and Methodology

The following environmental indicators from the General Programme Instructions of the International EPD (Environmental Product Declaration) System have been used in this study (see Table 2-5)(https://www.environdec.com/resources/indicators). The Water Scarcity Footprint (WSF) and the Abiotic Depletion Potential of both elements (ADPE) and fossil fuels (ADPF) have not been included due to them not being relevant to marine aquaculture.

Table 2-5: Environmental impact categories included in this study

Impact Category	Description	Unit	Reference
Global Warming Potential (GWP100) **GWP – fossil** **GWP – biogenic** **GWP – total**	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions absorb radiation (energy/heat) emitted by the earth. This radiation is subsequently re-emitted in all directions with the downward component responsible for warming the planet's surface, increasing the natural greenhouse effect. This may have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 eq.	(IPCC, 2013)
Ozone Depletion Potential (ODP)	A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth’s surface with detrimental effects on humans and plants.	kg CFC-11 equivalent	(Guinée, et al., 2002)
Acidification Potential (AP)	A measure of emissions that increase the acidity of the environment. Potential effects include increased fish mortality, decreased shellfish shell formation, forest decline, and the deterioration of building materials.	kg SO_2 eq.	(Hausschild & Wenzel, 1998)
Eutrophication Potential (EP)	A measure of the excessive addition of nutrients (such as nitrogen and phosphorus) to a water system resulting in increased aquatic plant and algal growth. This may cause an undesirable shift in species composition, an increase in toxins and depressed oxygen levels because of the additional consumption of oxygen in biomass decomposition.	kg Phosphate eq.	(Heijungs, et al., 1992)
Photochemical Oxidant Formation Potential (POFP)	A measure of emissions that contribute to air pollution in the form of smog. Smog or ground level ozone may be injurious to human health and ecosystems and may also damage crops.	kg NMVOC eq.	(van Zelm R, 2008)

2.8. Interpretation to Be Used

The results of the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA) were interpreted according to the Goal and Scope. The interpretation addresses the following topics:

- Identification of significant findings, such as the main process step(s), material(s), and/or emission(s) contributing to the overall results.
- Evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data.
- Conclusions, limitations and recommendations.

2.9. Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

- Measured primary data are considered to be of the highest precision, followed by calculated data, literature data, and estimated data. The goal is to model all relevant foreground processes using measured or calculated primary data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal was to capture all relevant data in this regard.
- Consistency refers to modelling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modelling choices, data sources, emission factors, or other artefacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report. The goal is to provide enough transparency with this report so that third parties are able to approximate the reported results. Using the available industry averages provided in section 3, the results shown in this report are reproducible.
- Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study’s goal and scope. The goal is to use the most representative primary data for all foreground processes and the most representative industry-average data for all background processes. Whenever such data were not available (e.g., no industry-average data available for a certain country), best-available proxy data were employed.

2.10. Type and Format of the Report

In accordance with the ISO requirements (ISO 14044 (2006b)) this document aims to report the results and conclusions of the LCA completely, accurately, and without bias to the intended audience. The results, data, methods, assumptions, and limitations are presented in a transparent manner and in sufficient detail to convey the complexities, limitations, and trade-offs inherent in the LCA to the reader. This allows the results to be interpreted and used in a manner consistent with the goals of the study.

2.11. Software and Database

The LCA model was created using the GaBi 10 Software system for life cycle engineering, developed by Sphera Solutions, Inc (Sphera, 2020). The GaBi 2020 LCI database provides the life cycle inventory data for the raw and process materials used in the modelling of the mussel and oyster lifecycle. The GaBi database is updated annually and contains over 15,000 datasets based on data from individual companies, industry associations and public bodies.

2.12. Critical Review

As this study is intended to provide comparative assertions that may be made available to the public, ISO 14040/44 requires that it undergo a critical review. This critical review has been conducted by a panel of three experts:

- Sarah McLaren, Professor of Life Cycle Management at Massey University (Chair)
- Friederike Ziegler, Associate Professor, RISE Research Institutes of Sweden
- Anna Farmery – Vice Chancellor’s Postdoctoral Research Fellow at the Australian National Centre for Ocean Resources and Security (ANCORS), University of Wollongong

The review took place in two parts – first a report containing the goal, scope, and proposed methodology was delivered during the beginning of data collection and then the full report was delivered once the LCA had been completed. This was done to allow the reviewers early input in the scope and methodology of the report to allow for adjustments early in the process.

The Critical Review Statement can be found in Annex A. The full commentary with the review panel can be found in Annex H. The panel has not viewed or reviewed the LCA models created in the GaBi LCA software for this project. The scope of their review focused on this report and the confidential data which support it.

3. Life Cycle Inventory Analysis

3.1. Data Collection Procedure

Given the large number of farms (several hundred) and the variability across farms in terms of size and location, a full LCA of the largest farmer and processer of both mussels and oysters was carried out as a first step. This information was used to identify the key environmental hotspots of the mussel and oyster life cycles so that a quantitative questionnaire for each sector could be developed. These questionnaires were then distributed to Aquaculture New Zealand associated farmers and processors of mussels and oysters in New Zealand. Not all farmers and processors responded to the questionnaires. A list of the respondents and the market share covered in this study is included in sections 3.2.3 and 3.3.3 for mussels and oysters respectively.

Primary data were collected using customised data collection templates, which were sent out by email to the respective data providers in the participating companies. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, and internal and external benchmarking. If gaps, outliers, or other inconsistencies occurred, thinkstep-anz engaged with the data provider to resolve any issues.

Wherever feasible, the coefficient of variation (CoV) was established for the different inputs and outputs across different data providers. This is a measure of the variability within a sample, providing an indication of how much variation there is between the average and the numbers used to calculate this average. It is calculated by dividing the standard deviation by the mean of that population. It is done to compare the variability of the data collected between different farmers and processors.

All data is shown with a Data Quality Indicator (DQI) and is used to show how the data has been collected, whether it be measured, calculated, estimated or from literature. Measured data is considered to be of higher quality, while estimated data is considered to be lower quality. Given that data is collected from a variety of farmers and processors, with different collection methods, the DQI has been selected based on the most common data collection method across all data providers.

This section presents the Life Cycle Inventory (LCI) across all farms and all processors weighted by their production mass. Not all farms or processors have the same types of inputs and outputs and, as a result, the LCI does not represent a specific farm or processor, but rather the weighted average of all respondents.

3.2. Mussels

3.2.1. Overview of Product System

Greenshell mussels are endemic to New Zealand and are commercially grown in the Coromandel, Golden Bay and Stewart Island. Mussel farmers source the juveniles, known as ‘spat’, by collecting spat that naturally washes up in beach-cast seaweed on Te Oneroa a Tōhe (Ninety Mile Beach) in Northland, from wild spat collected on spat-catching ropes in the marine environment, and from domesticated spat bred at the SPATnz hatchery in Nelson. Mussel spat collected on Te Oneroa a Tōhe is managed under New Zealand’s Quota Management System (QMS).

Spat are transported to mussel farms around New Zealand where they are mechanically ‘seeded’ onto spat ropes using cotton socking (which breaks down naturally as the mussels attach to the lines) and suspended under buoys using a subtidal ‘longline’ rope system. After three to six months, the nursery lines are lifted, and the young spat are stripped from the ropes. They are then reseeded on a final production rope at approximately 150 to 200 mussels per metre. Mussels get all their nutrients by filtering seawater, which sees them reach maturity in 12-24 months. When mussels grow to around 100mm in length and are in plump condition, they are harvested off the lines and transported for processing and shipping.

Included in this LCA are the:

- Sourcing of baby mussels (spat).
- Farming of the spat into adult mussels and harvesting of these mussels.
- Processing and packaging of harvested mussels.
  - Additional processing required to produce mussel oil and powder.
- Distribution to the consumer.
- Consumption (including cooking, if applicable).
- End-of-life disposal of the leftover mussel waste and packaging.

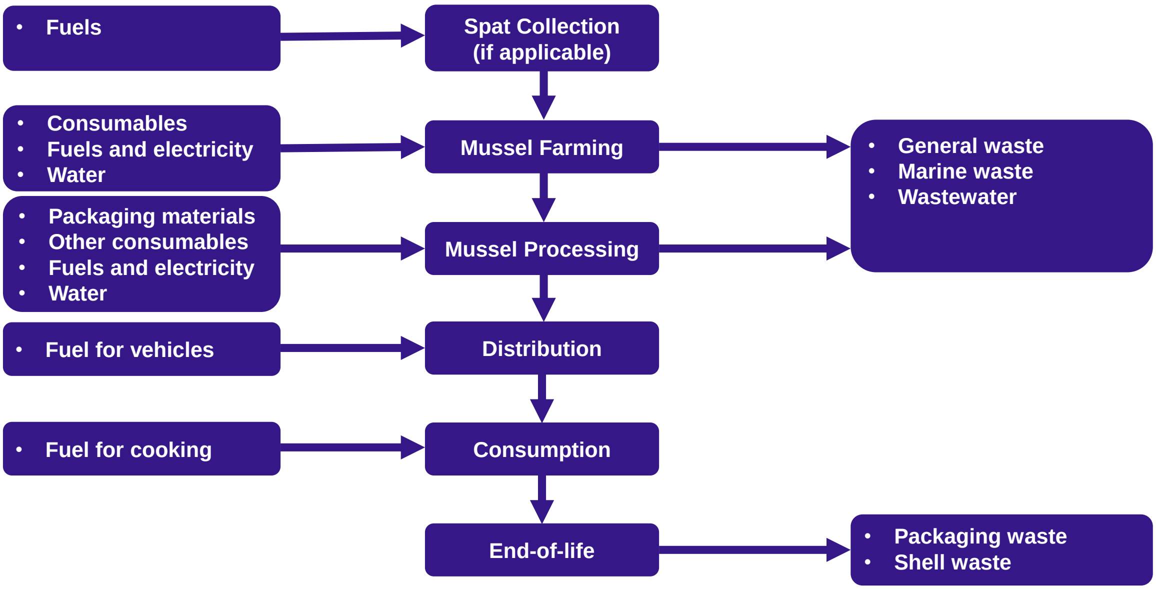

Figure 3-1: Life cycle diagram of mussels

3.2.2. Product Composition

The product considered in this section is one kilogram of Individually Quick Frozen (IQF) half shell mussels as well as the packaging associated with the mussels. The material composition of this product per 1 kilogram of edible meat is shown below in Table 3-1.

Table 3-1: Product and per one kilogram of edible meat

Product	Mussel meat	Shell
Frozen Half Shell Mussels	1	0.53
Live Mussels	1	1.05
Mussel Meat	1	0

3.2.3. Data Contributors

To ensure the validity of this study, data were sourced from a range of mussel farmers and processors. It is estimated that data was collected from mussel farms making up approximately 77 percent of the farming production in New Zealand in 2019, based on 2019 production data market share (Aquaculture NZ, 2020b). Processor data collected was estimated to make up approximately 70 percent of the processing volume in 2019.

Table 3-2: Data contributors

Company	Provider of farming data	Provider of processing data
Aroma Aquaculture	X	
Clearwater Mussels	X	
Gold Ridge Marine Farms	X	
Gulf Mussel Farms	X	
Kono Seafoods	X	X
MacLab NZ	X	
North Island Mussels Ltd (NIML)		X
Nelson Ranger Fishing Co (NRFC)	X	
OP Columbia		X
Sanford	X	X
Westpac Mussels	X	X

3.2.4. Spat Collection

There are three different methods for commercial mussel spat collection in New Zealand:

1. From beaches (~65 percent of spat collected)
2. On ropes (~25 percent)
3. From the SPATnz hatchery in Nelson (~10 percent) (Taylor, 2020).

In 2017, Te Oneroa-a-Tōhe (Ninety Mile Beach) accounted for about 65% of the mussel industry’s spat requirements (Ministry for Primary Industries, 2018). Due to the majority of spat collection taking place on beaches and the fact that the spat collection impacts account for a very small proportion of overall impacts, all spat collection was modelled as being from beach collection. Data was not able to be gathered for the other spat collection methods.

It is presumed that spat from beach collection is the collection method with the highest level of environment impact, particularly for GWP as it is the most active with vehicles required to travel to beaches which may be far away from the farms. Because of this, the approach of modelling all spat collection as from beaches is conservative. Ropes are considered to be passive method of collection with lower impacts, but diesel would be consumed putting out the ropes and during collection.

Te Oneroa-a-Tōhe beach spat collection involves picking up seaweed with the spat attached – either by hand or with machinery (loaders). Once the spat has been washed up on the beach it is outside its natural habitat and is unlikely to survive to grow into maturity to produce more spat. Because of this, the management and regulation of mussel spat is as a fishery, different to other aquaculture (Ministry for Primary Industries, 2018). As there are no consumables used in this process, the only LCI input considered was the diesel used by machinery – which include loaders, utes, and trucks and includes transport from the beach to the mussel farms.

Table 3-3: Diesel used per kg of spat collected

Input	Flow	Value	Unit	DQI*	COV**
Inputs	Diesel	8.85E-02	L	Measured	26%

* measured / calculated / estimated / literature

** coefficient of variation = (std deviation / arithmetic mean)

3.2.5. Mussel Farming

All mussel farming in New Zealand use variations of the longline mussel farming system. This involves the mussels being mechanically ‘seeded’ onto spat ropes using cotton socking and suspended on a subtidal longline rope system under buoys. After three to six months, the nursery lines are lifted and the young spat are stripped from the ropes and reseeded on a final production rope at approximately 150 to 200 mussels per metre.

As the mussels grow and become heavier, more floats are added to the line to stop the mussels sinking too low in the water. Fully-grown mussels (around 100mm length) are harvested after being on the production rope for 18 to 24 months. The data collected for this study covers a single calendar year rather than a full growth cycle. This choice was made in consultation with mussel farmers who indicated that because a consistent number of shellfish is farmed each year, the choice of a single year or multiple years should have little influence on the results.

Unwanted blue mussels (*Mytilus galloprovincialis*) are also pulled up with the green lipped mussels. From literature, 9% of the total mass of mussels harvested on the farm site are blue mussels (Forrest & Atalah, 2017). Most of these blue mussels are tossed overboard into the ocean during harvesting and are considered to be removed from the system. The modelling of interactions with the environment by mussels during shell formation is described in section 3.4. As there was no direct diesel data for the transportation of mussels from farm to processor, farmers were asked what the distance to the processing site was, with a weighted average from the respondents being 128 km.

Table 3-4 shows the Life Cycle Inventory (LCI) per kilogram of “Green Weight” greenshell mussels harvested. The term “green weight” refers to the live weight of mussels harvested, which includes some sea detritus which is not able to be removed on the boat.

Table 3-4: Mussel farming LCI (per kilogram of Green Weight (GW) mussels harvested)

Type	Flow	Value Unit	DQI*	COV**
Inputs	Spat collected from beach	5.75E-03 kg	Measured	±51%
	HDPE Floats made	1.40E-03 kg	Calculated	±73%
	HDPE Floats bought	6.33E-04 kg	Calculated	±319%
	Plastic tie-ons	5.82E-05 kg	Calculated	±748%
	Rope	9.44E-03 kg	Calculated	±239%
	Cotton seeding socking	3.69E-03 kg	Calculated	±81%
	Steel	3.14E-05 kg	Calculated	±87%
	Electricity	4.50E-03 kWh	Calculated	±94%
	LPG	1.41E-03 L	Calculated	±74%
	Diesel	3.70E-02 L	Calculated	±18%
	Lubricating oil	4.50E-05 kg	Calculated	±87%
	Petrol	4.06E-04 L	Calculated	±161%
	Municipal water	2.14E-02 kg	Calculated	±92%
	Rain water	8.94E-03 kg	Calculated	±202%
Outputs	GW mussels harvested	1.00E+00 kg	Measured	±0%
	Blue Mussels (to ocean)	9.89E-02 kg	Literature	±0%
	Wastewater- No treatment	2.14E-02 kg	Calculated	±92%
	Wastewater - Municipal	8.94E-03 kg	Calculated	±202%
	Plastic waste to landfill	1.01E-02 kg	Calculated	±225%
	General waste to landfill	3.78E-03 kg	Calculated	±80%
	Marine waste to landfill	6.31E-03 kg	Calculated	±87%
	Waste to recycling	1.40E-03 kg	Calculated	±73%

* measured / calculated / estimated / literature

** coefficient of variation = (std deviation / arithmetic mean)

3.2.6. Mussel Processing

The mussel processing stage involves the separation of the mussels from other growth such as seaweed and other sea detritus at specialised facilities. Post-harvest, most mussels are then further processed via heat treatment and then separation of one or both halves of the shell from the meat either by hand or with a machine. Packaging inputs for the products are shown in Table 3-5. Table 3-6 shows the inputs and outputs for the processing stage, per kilogram of equivalent whole mussels produced.

Table 3-5: Packaging of mussel products (per kilogram of product)

Packaging materials	Frozen half shell	Live	Potted Unit
Cardboard box	0.088	-	0.036 kg
Gel packs	-	0.110	- kg
Polybag	0.006	-	0.006 kg
Polystyrene box	-	0.077	- kg
Polypropylene pot	-	-	0.093 kg
Plastic trays (PET)	-	0.074	- kg

The “marine waste for cut-off” output in Table 3-6 is made up of mussel shells and other marine waste which is not sent to a landfill and is instead used elsewhere, for example in composting or a chicken grit. It should be noted that the industry is making an effort to divert waste from landfill by increasing the amount that is recycled and the current split of general waste going to landfill versus to recycling may be different from the one given.

Table 3-6: Mussel processing LCI (per kilogram of whole mussel equivalents processed)

Type	Flow	Value Unit	DQI*	COV**
Inputs	Mussels and sea detritus	1.41E+00 kg	Measured	±28%
	Shrink wrap	1.78E-05 kg	Calculated	±990%
	Electricity	3.26E-01 kWh	Measured	±50%
	Natural Gas	1.31E-02 MJ	Measured	±1289%
	Diesel (thermal energy)	2.92E-02 L	Measured	±86%
	Compressed Natural Gas	3.79E-01 MJ	Measured	±218%
	Total site energy use (all fuels and electricity, not including forklifts)	*2.79E+00 MJ*		*±23%*
	LPG (forklifts)	4.34E-06 L	Measured	±66%
	Diesel (forklifts)	4.21E-04 L	Measured	±135%
	R07c	4.26E-09 kg	Measured	±56%
	R22	2.83E-06 kg	Measured	±279%
	R32	3.62E-08 kg	Measured	±56%
	R404A	6.39E-06 kg	Measured	±403%
	R410	1.02E-07 kg	Measured	±56%
	Water - municipal	1.90E+01 kg	Measured	±31%
	Ammonia	1.60E-05 kg	Estimated	±120%
	Fossil lubricants	5.52E-04 kg	Estimated	±0%
	Biobased lubricants	1.30E-04 kg	Estimated	±0%
Outputs	Whole Mussel equivalents processed	1.00E+00 kg	Calculated	±0%
	Marine waste to landfill	3.57E-01 kg	Calculated	±80%
	Marine waste to cut-off	3.35E-03 kg	Calculated	±66%
	General waste to recycling	1.35E-02 kg	Estimated	±322%
	General waste to landfill	3.37E-02 kg	Estimated	±322%
	Wastewater - Municipal	1.84E+01 kg	Calculated	±28%
	Wastewater - No treatment	6.17E-01 kg	Calculated	±174%
	Ammonia to air	1.60E-05 kg	Calculated	±120%

3.2.7. Distribution

Transportation from processor to retailer

New Zealand mussel products are distributed to 77 countries across the world, (the United States and China are the two largest markets) with the transportation mode being dependent on the product. Live mussels are transported by plane, while frozen mussels and mussel products are shipped to their respective destinations. In the main results section in this report, the scenario considered is the NZ Domestic scenario show in Table 3-7. Export scenarios have been considered in section 4.4

The shipping and trucking distances of exported frozen and live mussels (Table 3-7) considers exported mussels and was calculated based on 2019 export statistics from Aquaculture NZ (Aquaculture NZ, 2020). This was calculated using a weighted average approach based on the percentage share of more than 90 percent of the export markets with distances calculated to their busiest port.. The export countries for all mussel products in 2019 can be seen in Figure 3-2, with the United States of America being shown as the largest single market. (Aquaculture NZ, 2020).

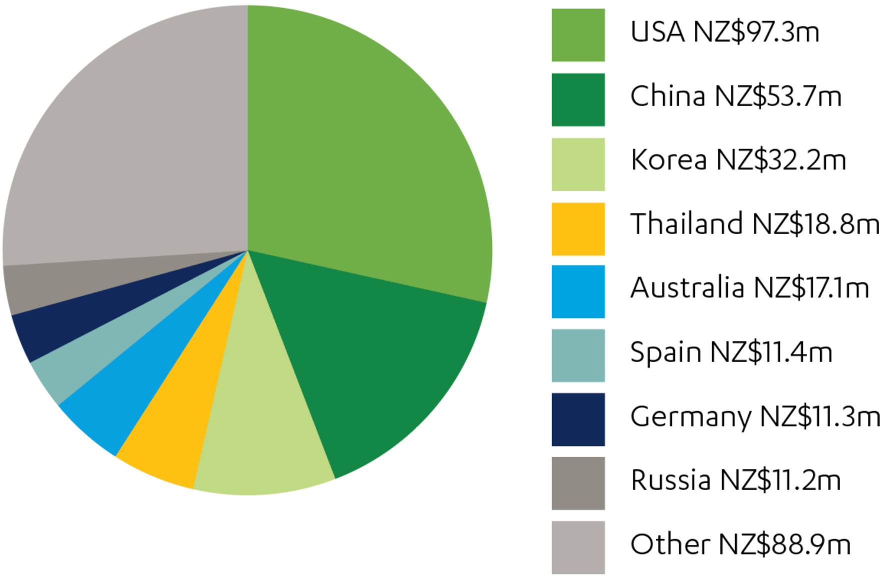

Figure 3-2: Export markets for mussel products in 2019 (Aquaculture New Zealand, 2020c)

Table 3-7: Mussel distribution distances to market

Product	Scenario	Flight distance (km)	Shipping distance (km)	Trucking distance (km)
Frozen Mussels	NZ Domestic	0	0	300
	Minimum Distance	0	2,159	300
	Sales Weighted Average	0	11,739	202
	Maximum Distance	0	21,648	300
Live Mussels	NZ Domestic	0	0	300
	Minimum Distance	4,411	0	100
	Sales Weighted Average	9,489	0	270
	Maximum Distance	10,911	0	300

The truck distance travelled in each country was modelled as 300 kilometres for destination countries with a land area larger than 1.9 million square kilometres (approximately the size of Mexico) and 100 kilometres for countries with a land area less than this.

To calculate the impacts of refrigerated shipping containers, the distance travelled by the mussels has been increased by approximately 23.4 percent due to the increased energy requirements of refrigeration. This is based on research by Fitzgerald et al. (2011) which found that on average (mean), 19 percent of the total energy consumption of a refrigerated container is used to refrigerate the cargo, while 81 percent of the energy is used for transportation. This results in an effective emission factor of 0.014 kg CO_2 per tonne kilometre (t.km), compared to the 0.013 kg CO_2 / t.km value used for refrigerated cargo in the Measuring Emissions: A Detailed Guide for organisations document (Ministry for the Environment, 2020). Live mussel products which are flown around the world are kept cold with gel packs.

Retail storage

Retail storage of frozen products has been estimated to be four weeks, following the Product Environmental Footprint Category Rules (PEFCR) guidelines (section 7.15.2) (European Commission, 2018). This has been modelled using a GaBi default process with the duration set to 28 days. The electricity grid mix has been modelled as the New Zealand national mix for domestic sales. Refrigerant gases emitted during retail storage also follow the PEFCR guidelines, modelled as R404a. Documentation of these datasets can be found in section 3.5.5.

Distribution losses/waste

Live shellfish undergo notable wastage throughout the distribution chain, particularly at the retailing level. The distribution chain wastage for live and potted shellfish has been estimated to be 9.3%, taken from a report but the United States Department of Agriculture (USDA, 2009). For potted shellfish this is almost certainly overestimating the wastage. This distribution wastage is shown in a separate category to the rest of the distribution impacts.

No losses/waste have been modelled for frozen products.

3.2.8. Use Phase

Transportation from retailer to consumer

The distance travelled by the product from the retailer to the consumer is modelled as five kilometres by passenger car. This transportation mode is different to what is recommended by the PEFCR guidelines (section 7.14.3) which recommends 62 percent of the product is transported by car, 5 percent by van, with 33 percent having no impact from transport (European Commission, 2018). This decision was made due to transportation by car being more common in New Zealand (the baseline scenario for mussels) compared to Europe, where the PEFCR guidelines were created. This does not have a significant impact on the results.

The allocation factor in this case is the percentage of the impacts of transportation assigned to the product. This reflects the fact that this process does not occur solely based on the output. For example, a car might drive to the shops and buy several items. The allocation factor has been determined following the PEFCR guidelines, where the volume of the product (and its packaging) is divided by 0.2 m^3 (which is a third of a trunk of 0.6 m^3). It has been estimated that 1 kilogram of half shell mussels and its packaging takes up approximately 0.01 m^3 of space, so the allocation factor of the product is 5 percent of the operation of the car.

Cooking

A kilogram of mussel meat has been modelled as being heated for 6 minutes in a 2.4 kW oven at 160°C, with 5 minutes of pre-heating time. The oven has been modelled as using electricity from the New Zealand electricity grid for domestic products and electricity from the United States electricity grid for export products. The United States was chosen is the largest market for mussels (see Figure 3-2). The cooking time is based on the cooking instructions on the back of a packet of Sanford Greenshell Mussels. All mussel products are assumed to be cooked in the same way.

3.2.9. End-of-life

The study model all mussel meat as having been eaten by the consumer and thereafter is considered to be outside the system boundary, as seen in Table 3-8. All other waste is assumed to be landfilled, apart from 50% of the cardboard packaging, which is modelled as being recycled. The location of end-of-life is modelled as in the United States, which is the largest market for mussels (see Figure 3-2). A breakdown of the masses reaching end-of-life fate is shown in Table 3-8. Waste to landfill is modelled as being transported by truck for 50 kilometres with a utilisation rate (load factor) of 50 percent. The dataset used can be found in Table 3-24.

The end-of-life of packaging results are included in the packaging stage of the results due to cardboard sequestering carbon during production, which needs to be accounted for in the “cradle-to-retail” values that are provided for the comparison to other protein sources.

Table 3-8: End of life of fate mussel product and packaging

Flow	EOL fate
Mussel meat	Cut-off (consumed)
Shell	Landfill
Cardboard packaging	50% Landfill, 50% Recycled
Plastic packaging	Landfill

3.3. Pacific Oysters

3.3.1. Overview of Product System

Pacific oysters were most likely introduced into New Zealand in the 1950s, with commercial farming starting sometime after this (Wassilieff, 2006). The Pacific oysters farmed in New Zealand are mostly grown in intertidal zones in the warmer waters around the top of the North island on racks, trays and in baskets. Since the 1960s, native rock oysters had been collected on sticks and then placed onto wooden racks and, after becoming established in New Zealand, pacific oysters quickly took the place of these native rock oysters due to their faster growth. This provides economic benefits to the oyster industry, but Pacific Oysters are also considered an invasive species (Troup, 2006).

Nowadays, the industry is evolving to farming selectively bred hatchery-raised spat in specialised basket and bag systems, to produce high-value and consistent oysters. Oysters are filter feeders and take all their nutrients from the water and are ready for harvest after 12-20 months. The data collected for this study covers a single calendar year, which is still applicable due to the relatively consistent number of shellfish being farmed year on year.

Included in this LCA are the:

- Collection of baby oysters (spat).
- Farming of the spat into adult oysters and the harvesting of these oysters.
- Processing of the oysters, removal of shells if applicable
- Distribution to the consumer.
- Consumption (i.e. cooking if applicable).
- End-of-life of the leftover oyster waste and packaging.

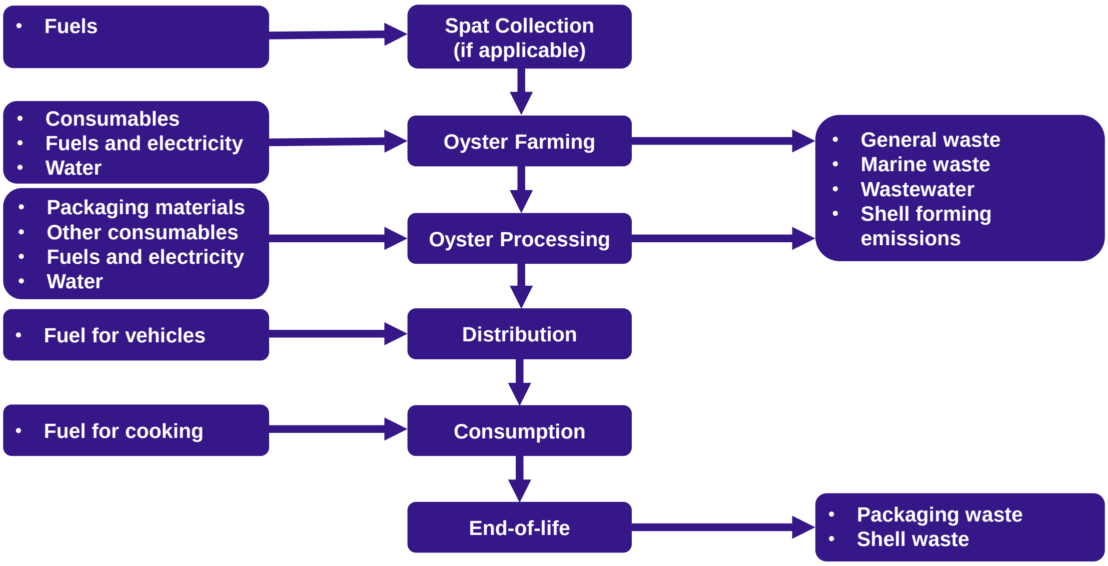

Figure 3-3: Life cycle diagram of oysters

3.3.2. Product Composition

The product considered in this section is one kilogram of fresh half shell oysters as well as the packaging associated with the oysters. The material composition of this product per 1 kilogram of edible meat is shown below in Table 3-9. One kilogram of meat is equivalent to the meat found in 6.01 dozen oysters.

Table 3-9: Product and per one kilogram of edible meat

Product	Mussel meat	Shell
Frozen Half Shell Oysters	1	1.90
Live Oysters	1	3.81
Oysters Meat	1	0

3.3.3. Data Contributors

To ensure the validity of this study, data were sourced from a range of oyster farmers and processors. Data were collected from oyster farms making up approximately 74 percent of the farming production in New Zealand in 2019, based on 2019 production market share (Aquaculture NZ, 2020b). Processor data collected was estimated to make up approximately 69 percent of the processing volume in 2019.

Table 3-10: Data contributors

Company	Provider of farming data	Provider of processing data
Biomarine Oysters	X	X
Clevedon Coast Oysters	X	X
Moana New Zealand	X	X
Taniwha Oysters	X	

3.3.4. Spat Production (from Hatchery)

Oyster spat comes from one of two sources: wooden sticks set by farmers in the inshore marine environment (onto which spat settles naturally) or from a single hatchery in Nelson that services farms across New Zealand. The diesel used in trucks to transport oyster spat from the hatchery to the rest of the country is included in the farming data as it was not possible to separate out from the rest of the farming data.

As the wooden stick and diesel data are included in the farming inventory and cannot be separated from the rest of the farming data, only the hatchery inputs are considered in this section. The electricity used in the spat hatchery process can be seen in Table 3-11. This is provided per dozen mature oysters harvested, which takes into account the percentage of oyster spat which do not reach maturity.

Table 3-11: Electricity used per dozen full mature oysters harvested in hatchery

Input	Flow	Value	Unit	DQI*
Inputs	Electricity	1.18E-01	kWh	Measured

* measured / calculated / estimated / literature

3.3.5. Oyster Farming

Oyster spat are typically on-grown on sticks, trays or netting bags in intertidal farms. Wooden sticks are nailed onto racks built so that the oysters sit just above water level at low tide. Some are grown in deeper waters; in trays or baskets beneath the surface or on longlines supported by buoys, similar to the way that mussels are grown. In New Zealand, this method is being phased in, as the wooden stick method is phased out. Data from both methods were used in this analysis.

Oysters grow by filter-feeding on phytoplankton that is washed tidally through the inlets. No external source of feed is required. The modelling of interactions with the environment by oysters during shell formation are described in section 3.4.

Table 3-12: Oyster farming LCI (per dozen oysters farmed)

Type	Flow	Value	Unit	DQI*	COV**
Inputs	Spat collected from hatchery	5.81E-01	doz	Calculated	74%
	Spat collected from harbour	4.19E-01	doz	Calculated	102%
	Cable ties	1.22E-05	kg	Calculated	99%
	HDPE mesh bag	4.15E-03	kg	Calculated	86%
	Skip bins	1.53E-03	kg	Calculated	126%
	Treated wood	4.89E-02	kg	Calculated	278%
	HDPE Trays	1.63E-04	kg	Measured	525%
	Electricity	6.57E-02	kWh	Measured	50%
	Petrol	4.33E-02	L	Measured	90%
	Diesel	1.99E-02	L	Measured	174%
	Diesel for trucks to processor	5.51E-02	L	Estimated	59%
Outputs	Oysters farmed	1.00E+00	doz	Measured	0%
	Plastic waste on landfill	5.86E-03	kg	Calculated	108%
	Wood waste on landfill	4.89E-02	kg	Calculated	278%

* measured / calculated / estimated / literature

** coefficient of variation = (std deviation / arithmetic mean)

3.3.6. Oyster Processing

The oyster processing stage involves the shucking of oysters into half shells or separating the meat entirely at specialised facilities. The packaging for each product can be found in Table 3-14, based on the data provided by contributors.

Table 3-13: Oyster processing LCI (per dozen oysters processed)

Type	Flow	Value	Unit	DQI*	COV**
Inputs	Oyster processing input	1.00E+00	doz	Measured	0%
	Salt	1.75E-04	kg	Measured	64%
	Shrink wrap	1.15E-03	kg	Calculated	62%
	Chilltainers	1.84E-03	kg	Calculated	64%
	Pallets	4.97E-03	kg	Calculated	0%
	Electricity	7.36E-01	kWh	Measured	14%
	LPG (forklifts)	1.23E-03	kg	Measured	64%
	Diesel (forklifts)	3.36E-03	L	Measured	224%
	Water - municipal	1.72E+01	kg	Calculated	64%
	Water - bore	3.64E+00	kg	Calculated	224%
Outputs	Dozen oysters processed	1.00E+00	doz	Measured	0%
	Wood waste on landfill	4.97E-03	kg	Calculated	0%
	General waste on landfill	8.57E-03	kg	Calculated	218%
	Wastewater - municipal	1.73E+01	kg	Calculated	62%
	Wastewater - biofield	3.49E+00	kg	Calculated	224%

* measured / calculated / estimated / literature

** coefficient of variation = (std deviation / arithmetic mean)

Table 3-14: Packaging of oyster products (per dozen oysters)

Packaging materials	Frozen half shell	Live	Potted Unit	
Cardboard box	0.028	-	-	kg
Gel packs	-	0.100	-	kg
Polybag	-	-	-	kg
Polystyrene box	-	0.046	0.033	kg
Polypropylene pot	-	-	0.021	kg
Plastic trays (PET)	0.013	0.013	-	kg

3.3.7. Distribution

Transportation from processor to retailer

New Zealand Oyster products are distributed to around 27 countries across the world with Australia being the largest market for frozen oysters while China is the largest markets for live oysters (Aquaculture NZ, 2020).The transportation mode is dependent on the product, with live and chilled oysters transported as air freight, while frozen oysters are generally sent as sea freight. In the main results section in this report, the scenario considered is the NZ Domestic scenario shown in Table 3-15. Export scenarios have been considered in section 4.4.

The distribution shipping and trucking distances of exported products were calculated based on 2019 export statistics from Aquaculture NZ (Aquaculture NZ, 2020). The export countries for all oyster products in 2019 can be seen in Figure 3-2, with Australia being shown as the largest single market.

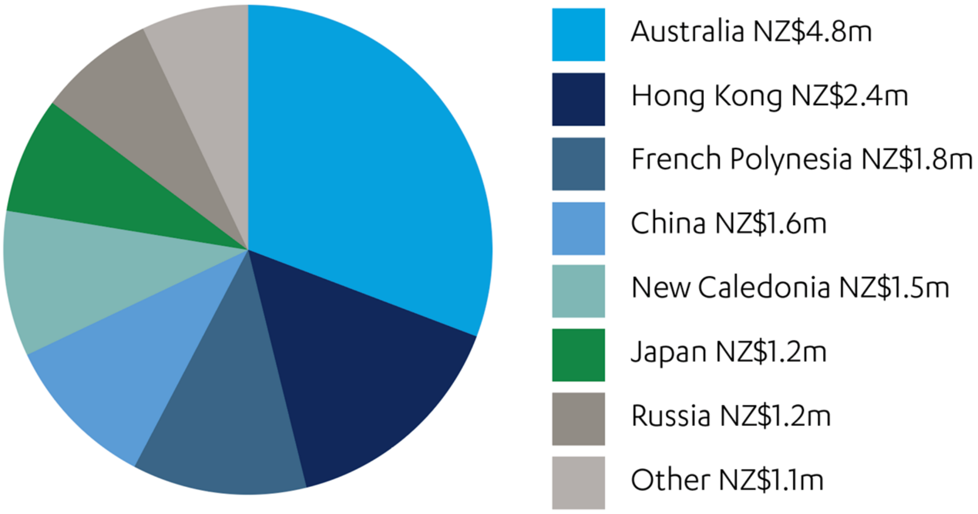

Figure 3-4: Export markets for oyster products in 2019 (Aquaculture New Zealand, 2020c)

Table 3-15: Oyster distribution distances to market

Product	Scenario	Flight distance (km)	Shipping distance (km)	Trucking distance (km)
Frozen oysters	NZ Domestic	0	0	300
	Minimum Distance	0	2,159	300
	Sales Weighted Average	0	5,435	205
	Maximum Distance	0	21,814	100
Live oysters	NZ Domestic	0	0	300
	Minimum Distance	0	2,105	300
	Sales Weighted Average	9,812	0	214
	Maximum Distance	16,459	0	300

The truck distance travelled in each country was modelled as 300km for destination countries with a land area larger than 1.9 million km^2 (approximately the size of Mexico) and 100km for countries with a land area less than this.

To calculate the impacts of refrigerated shipping containers, the distance travelled by the oysters has been increased by approximately 23.4 percent due to the increased energy requirements of refrigeration. This is based on research by Fitzgerald et al. (2011) which found that on average (mean), 19 percent of the total energy consumption of a refrigerated container is used to refrigerate the cargo, while 81 percent of the energy is used for transportation. This results in an effective emission factor of 0.014 kg CO_2 per tonne kilometre (t.km), compared to the 0.013 kg CO_2 / t.km value used for refrigerated cargo in the Measuring Emissions: A Detailed Guide for organisations document (Ministry for the Environment, 2020). Live oysters, which are flown around the world are kept cold with gel packs.

Retail storage

Retail storage of frozen products has been estimated to be 4 weeks, following the Product Environmental Footprint Category Rules (PEFCR) guidelines (section 7.15.2) (European Commission, 2018). This has been modelled using a GaBi default process with the duration set to 28 days. The electricity grid mix has been modelled as the New Zealand national mix for domestic sales. Refrigerant gases emitted during retail storage also follow the PEFCR guidelines, modelled as R404a. Documentation of these datasets can be found in section 3.5.5.

Distribution losses/waste

Live shellfish undergo notable wastage throughout the distribution chain, particularly at the retailing level. The distribution chain wastage for live and potted shellfish has been estimated to be 9.3%, taken from a report but the United States Department of Agriculture (USDA, 2009). This distribution wastage is shown in a separate category to the rest of the distribution impacts.

No losses/waste have been modelled for frozen products.

3.3.8. Use Phase

Transportation from retailer to consumer

The distance travelled by the product from the retailer to the consumer is modelled as five kilometres by passenger car. This transportation mode is different to what is recommended by the PEFCR guidelines (section 7.14.3) which recommends that 62 percent of the product is transported by car, 5 percent by van, with 33 percent having no impact from transport (European Commission, 2018). This decision was made due to transportation by car being more common in New Zealand (the baseline sales location for oysters) compared to Europe, where the PEFCR guidelines were created. This does not have a significant impact on the results.

The allocation factor in this case is the percentage of the impacts of transportation assigned to the product. This reflects the fact that this process does not occur solely based on the output. For example, a car might drive to the shops and buy several items. The allocation factor has been determined following the PEFCR guidelines, where the volume of the product (and its packaging) is divided by 0.2 m^3 (which is a third of a trunk of 0.6 m^3). It has been estimated that 1 kilogram of half shell oysters and its packaging takes up approximately 0.01 m^3 of space, so the allocation factor of the product is 5 percent of operating the car.

Cooking

Unlike mussels, oysters are usually consumed raw. No cooking impacts have been applied for oysters.

3.3.9. End-of-life

It has been modelled that all oyster meat is eaten by the consumer and is thereafter considered to be outside the system boundary, as seen in Table 3-16. All other waste is assumed to be landfilled, apart from 50% of the cardboard packaging, which is modelled as being recycled. The location of end-of-life is modelled as Australia, which is the biggest market for oysters (see section 3.3.7). Product and packaging composition at end-of-life is shown in section 3.3.2. Waste to landfill is modelled as being transported by truck for 50 kilometres with a utilisation rate (load factor) of 50 percent. The dataset used can be found in Table 3-24.

The end-of-life of packaging results are included in the packaging stage of the results due to cardboard sequestering carbon during production, which needs to be accounted for in the "cradle-to-retail" values that are provided for the comparison to other protein sources.

Table 3-16: End of life fate of oyster product and packaging

Flow	EOL fate
Oyster meat	Cut-off (consumed)
Shell	Landfill
Paper packaging	50% Landfill, 50% Recycled
Plastic packaging	Landfill

3.4. Interactions with the Environment

While mussels and oysters do not require human intervention to grow in the ocean, they do have a direct impact on the chemistry of the ocean through the feeding and shell formation processes. The main interactions with the environment include:

- Carbon cycle:
  - Flesh formation.
  - Shell formation.
  - Shell dissolution at end-of-life.
- Nitrogen cycle:
  - Gaseous nitrous oxide release through incomplete denitrification.
  - Uptake of nitrogen compounds during bivalve filter feeding.

One area of confusion when it comes to the Life Cycle Assessment of shellfish is the chemical reaction which occur during the formation of the shell. A common misconception is that because the shell contains carbon (in the form of calcium carbonate, $CaCO_3$), it must therefore be sequestering carbon dioxide (CO_2). However, studies show that the reaction which takes places also *releases* carbon dioxide, as can be seen in Equation 1. Not all the carbon dioxide formed in this reaction reaches the atmosphere, due to buffering which occurs in seawater in the complex oceanic carbonate system. This relationship of released CO_2 to precipitated carbonate, called *psi* (ψ), is calculated as 0.694492 in this study (see Annex C for more information)

$$Ca^{2+} + 2HCO_3^- \rightleftharpoons CaCO_3 + CO_2 + H_2O$$

Equation 1: Shell formation reaction

For shellfish flesh formation, this study assumes that flesh is formed from carbon absorbed from the water column. Furthermore, this study assumes that all flesh is consumed and converted to CO_2, meaning that the flesh is carbon neutral over its full life cycle.

The nitrogen uptake from the water column was initially considered as having a potential positive impact on the eutrophication potential indicator (i.e., decreasing it). However, due to significant uncertainties, nitrogen uptake has not been included in the final results (conservative approach). The major uncertainty is differences in the regional availability of nitrogen in New Zealand coastal waters (some areas are already lacking nitrogen). Furthermore, the eutrophication indicator used in this study does not support the uptake of nitrogen compounds as a negative value. This is suggested as an area for further study for the New Zealand shellfish industry

These interactions are further described in Annex C for carbon and Annex E for nitrogen. The mitigation potential of the shell formation carbon release is found in Annex D.

3.4.1. Ocean Acidity

Releases of CO_2 to water are not considered as a contributor to the Acidification Potential indicator used in this study, as the methodology applied focuses on acidifying emissions to air only, which may later contribute to acidification in terrestrial, freshwater aquatic, and marine environments, but it does not consider direct emissions to water. As there is no acidification of oceans methodology widely accepted and ocean acidification is closely linked to carbon dioxide release (tracked by the GWP indicator), results for this have not been calculated.

An increase in ocean acidity in recent times has been linked to the excessive anthropogenic releases of carbon dioxide into the atmosphere. It has been estimated that more than 25% of the carbon dioxide released by fossil fuels is absorbed by the ocean, leading to sea water becoming 30% more acidic (Smithsonian Institute, 2018). This causes direct problems for all sea life, especially shellfish as it makes it harder for them to grow their shells. In order to reduce the impacts of ocean acidification, reductions in carbon dioxide emissions must be made.

3.5. Background Data

The most relevant LCI datasets used in modelling the product systems are detailed below. New Zealand average data sets were used when available. All background datasets were obtained from the GaBi LCI Database 2020 and documentation can be found at: http://www.gabi-software.com/support/gabi/gabi-database-2020-lci-documentation.

Note that all GaBi datasets have their upstream energy (and any upstream energy present in their upstream materials) updated at least annually. In addition, all GaBi datasets are updated whenever the technology or geographical mix of the producers of a product changes significantly.

The proxy column is used to indicate whether a dataset accurately represents the desired material or process; a No* indicates the use of a geographical proxy for a correct dataset where the region of manufacture is expected to have little influence on its environmental profile; and a Yes* indicates the use of a geographical proxy for a correct dataset where the region of manufacture is expected to materially influence its environmental profile.

3.5.1. Fuels and Energy

National averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2020 databases. If New Zealand datasets were not available, Australian datasets were used and European datasets were used if neither of these were available. Table 3-17 shows the most relevant datasets used in modelling the product systems. Documentation for all GaBi datasets can be found at http://www.gabi-software.com/support/gabi/gabi-database-2020-lci-documentation/.

Table 3-17: Key energy datasets used in inventory analysis

Energy	Location	Dataset	Data Provider	Reference Year	Proxy?
Electricity	NZ	Electricity grid mix	Sphera	2016	No
Natural gas	NZ	Thermal energy from natural gas	Sphera	2016	No
LPG	EU	Thermal energy from LPG	Sphera	2016	No*
Diesel	AU	Diesel mix at filling station	Sphera	2016	No*
	GLO	Diesel combustion in forest engine	Sphera	2018	No
CNG	NZ	Thermal energy from natural gas	Sphera	2016	No
	GLO	Compressed natural gas (CNG)	Sphera	2016	No

3.5.2. Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2020 database. Table 3-18 shows the most relevant LCI datasets used in modelling the product systems. Documentation for all GaBi datasets can be found at http://www.gabi-software.com/support/gabi/gabi-database-2020-lci-documentation/ .

Table 3-18: Key material and process datasets used in inventory analysis

Material/ process	Location	Dataset	Data Provider	Reference Year	Proxy?
Steel wire	DE	Steel wire rod	Sphera	2019	Yes*
Plastic granulate	CN	Polyethylene high density granulate	Sphera	2019	No
Cotton sockings	DE	Cotton raw conventional	Sphera	2019	Yes*
	US	Cotton yarn – open raw input	Sphera	2019	Yes*
Polypropylene rope	IN	Polypropylene fibres	Sphera	2019	No*
Fossil fuel lubricant	AU	Lubricants at refinery	Sphera	2019	No*
Bio-based lubricant	GLO	Lubricant (aqueous emulsion of fatty substances)	Sphera	2019	No
Plastic film	CN	Polyethylene film (PE-HD) (without additives)	Sphera	2019	No
Cardboard	EU-28	Corrugated cardboard 2015, average composition	FEFCO	2015	Yes*
Ammonia	CN	Ammonia (NH_3) without CO_2 recovery	Sphera	2019	No
R32	EU-28	R32 – Difluoromethane	Sphera	2019	Yes*
R410A	EU-28	Refrigerant R410A	Sphera	2019	Yes*
R407C	EU-28	Refrigerant R407C	Sphera	2019	Yes*
R404A	EU-28	Refrigerant R404A	Sphera	2019	Yes*
R22	EU-28	Chlorodifluoromethane (R22, HCFC-22)	Sphera	2019	Yes*
Municipal water	NZ	Tap water from surface water (for regionalisation)	Sphera	2019	Yes*

3.5.3. Transportation

Average transportation distances and modes of transport are included for the transport of the raw materials, operating materials, and auxiliary materials to production and assembly facilities.

The GaBi 2020 database was used to model transportation using the GaBi global transportation datasets. Fuels were modelled using the geographically appropriate datasets.

Table 3-19: Transportation and road fuel datasets

Mode / fuels	Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
Diesel forklift	AU	Diesel mix at filling station	Sphera	2016	No*
	GLO	Diesel combustion forklift	Sphera	2018	No
Truck	GLO	Truck, Euro 0 - 6 mix, 20 - 26t gross weight / 17.3t payload capacity	Sphera	2019	No
Diesel	AU	Diesel mix at filling station	Sphera	2013	No*
Container ship	GLO	Container ship, 5,000 to 200,000 dwt payload capacity, ocean going	Sphera	2019	
Heavy fuel oil	AU	Heavy fuel oil at refinery (1.0 wt. % S)	Sphera	2016	
Aircraft freight	GLO	Cargo plane, 113 t payload	Sphera	2019	No
Jet fuel	AU	Kerosene / Jet A1 at refinery	Sphera	2016	No*

3.5.4. Packaging

The datasets used for modelling product packaging materials are provided in Table 3-20.

Table 3-20: Key material and process datasets used in packaging

Material/ process	Location	Dataset	Data Provider	Reference Year	Proxy?
Cardboard	EU-28	Corrugated board excl. paper production 2015, open paper input, average composition	Sphera/ FEFCO	2015	No*
	EU-28	Testliner (2015) - for use in cut-off EoL scenario cases	Sphera/ FEFCO	2015	No*
Polyethylene terephthalate	CN	Polyethylene terephthalate granulate (PET) via DMT	Sphera	2019	No
	CN	Electricity grid 1kV-60kV	Sphera	2016	No
Expanded polystyrene	CN	Expanded polystyrene (EPS 15)	Sphera	2019	No
Shrink wrap	CN	Polyethylene film (LDPE/PE-LD)	Sphera	2019	No*
Polypropylene	CN	Polypropylene granulate	Sphera	2019	No*
Thermoforming	GLO	Plastic thermoformed part	Sphera	2019	No*
Gel packs	CN	Polyethylene film (LDPE/PE-LD)	Sphera	2019	No*
	CN	Water, from tap	Sphera	2019	No*
	DE	Propylene glycol	Sphera	2019	No*

3.5.5. Retail Storage

The datasets used for modelling retail storage are provided in Table 3-21.

Table 3-21: Retail storage processes

Process	Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
Storage of food products in cold store	GLO	Chilled & frozen cold storage	Sphera	2019	No
R404a	EU-28	EU-28: R404a	Sphera	2019	Yes*
Electricity	US	US: Electricity grid mix	Sphera	2016	No
Electricity	AU	AU: Electricity grid mix	Sphera	2016	No

3.5.6. Use Phase

The datasets used for modelling the consumer stage are provided in Table 3-22.

Table 3-22: Consumer processes

Process	Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
Passenger car travel (petrol and diesel mix)	GLO	Passenger car, average, Euro 3-5, engine size from 1.4l up to >2l	Sphera	2019	No
Electricity	US	US: Electricity grid mix	Sphera	2016	No
Electricity	AU	AU: Electricity grid mix	Sphera	2016	No
Electricity	NZ	Electricity grid mix	Sphera	2016	No

3.5.7. Waste and Wastewater Treatment Processes

The datasets used for modelling wastewater treatment are provided in Table 3-23.

Table 3-23: Waste treatment processes

Treatment/ Process	Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
Municipal wastewater treatment	GLO	Municipal wastewater treatment (sludge landfill, for regionalization)	Sphera	2019	No
	NZ	Electricity grid mix (1kV-60kV)	Sphera	2016	No
	NZ	Thermal energy from natural gas	Sphera	2016	No
General waste	EU-28	Municipal solid waste on landfill	Sphera	2019	No*

3.5.8. End-of-life

The processes used for the product and packaging end-of-life are shown in Table 3-24.

Table 3-24: End-of-life processes

Process	Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
Mussel meat - post consumer	N/A	Cut-off			No
Oyster meat – post consumer	N/A	Cut-off			No
Shell waste – post consumer	US	Glass/inert on landfill	Sphera	2019	Yes
Plastic packaging waste	US	Plastic waste on landfill, post-consumer	Sphera	2019	No
Paper packaging waste	US	Paper water on landfill, post-consumer	Sphera	2019	No
Truck – Medium Heavy-duty Diesel	US	Truck – Euro 0-6 Mix, 14-20t gross weight / 11.4t payload capacity	Sphera	2019	No

4. Life Cycle Impact Assessment

This chapter contains the results for the environmental impact categories defined in section 2.7. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions were to behave like they are modelled. In addition, the inventory only captures the fraction of the total environmental load that corresponds to the chosen functional unit (in this case either 1 kg of shellfish meat or 100 g of edible protein).

Life Cycle Impact Assessment (LCIA) results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks. Table 4-1 shows the abbreviations used for the indicators considered in this section. A description of these indicators can be found in section 2.7.

Table 4-1: Indicator abbreviations

Impact indicator	Abbreviation
Global warming potential (total)	GWPT
Global warming potential (fossil)	GWPF
Global warming potential (biogenic)	GWPB
Global warming potential (land use and land use change)	GWPLULUC
Global warming potential (aviation)	GWPA
Acidification potential	AP
Eutrophication potential	EP
Photochemical ozone formation potential	POFP

GWPB is further broken down into GWPB and GWPB-Product. GWPB-Product represents the biogenic carbon flows due to the carbon contained within the shellfish flesh, while GWPB represents all other biogenic carbon flows that are not directly linked to the shellfish flesh.

4.1. Assessment Results

4.1.1. Mussels – Environmental Impact Indicators

The impacts of mussels sold in New Zealand across their full life cycle can be seen in Figure 4-1 and Table 4-2 to Table 4-4.

Farming is the most significant stage in terms of GWPT, due largely to the carbon dioxide released during shell formation and the vessel diesel usage in this stage (see Table 4-8 for more information). The farming stage in Table 4-2, Table 4-3 and Table 4-4 includes the sequestration of carbon in the meat of the mussel, which is not included in the cradle-to-gate value used in section 4.3.2 for the comparison to other protein sources. The carbon dioxide release during shell formation is counterintuitive due to the presence of carbon in the shell (in the form of calcium carbonate). This release occurs because carbon dioxide is a by-product of the chemical reaction that forms calcium carbonate in seawater (see section 3.4 and Annex C for more information). The End-of-Life impacts of potted meat are zero apart from the release of biogenic carbon in the meat. This is due to the packaging waste disposal impacts being included in the packaging section and there being no shell to dispose of.

The main difference in carbon footprints between products is from the different types of packaging used for each product type. Frozen half shell mussels are supplied in cardboard boxes with a plastic bag inside, which have low impacts due to the low weight per kilogram of product (see Table 3-5) as well as cardboard being a relatively low-carbon packaging material. Live product is modelled as being supplied on plastic trays inside polystyrene boxes. As live mussels take up more volume than frozen half shell mussels, more packaging per kilogram of product is required.

Furthermore, the product waste and/or loss rate applied to fresh products (live and potted meat) is relatively large (9.3%) compared to that assumed for frozen products (0%) – see section 3.2.7. The impact of all the upstream impacts of wasted product is shown in the “distribution wastage” stage, which follows the principle of modularity, commonly used in LCA.

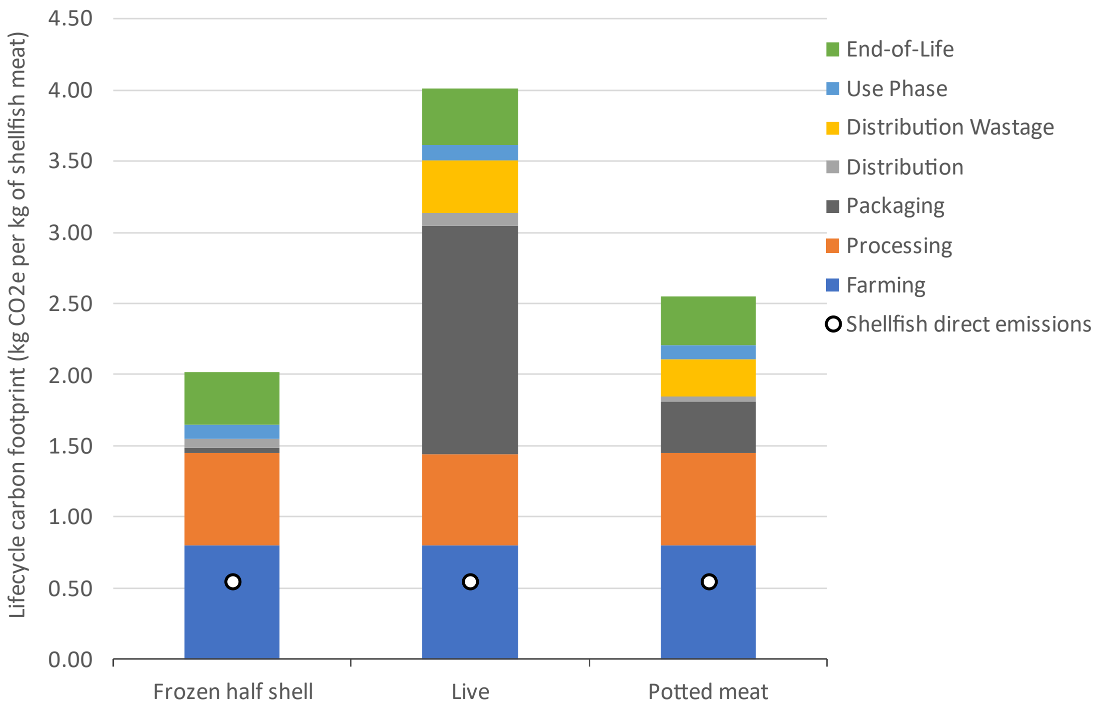

Figure 4-1: Total GWP of 1 kilogram of mussel products, New Zealand distribution (kg CO_2e per kilogram of meat) Shellfish direct emissions refer mainly to emissions from shell formation

Table 4-2: Environmental impacts of frozen half shell mussels, New Zealand distribution (per 1 kg of meat)

Impact indicator	Unit	Farming	Processing	Packaging	Distribution	Use Phase	End-of-Life	Total	CoV
GWPT	kg CO$_2$-eq.	0.796	0.650	0.0396	0.0595	0.106	0.369	2.02	±38%
GWPF	kg CO$_2$-eq.	0.586	0.461	0.144	0.0581	0.104	0.0268	1.38	±48%
GWPB	kg CO$_2$-eq.	0.553	0.188	-0.106	0.00129	7.22E-04	-0.00103	0.636	±18%
GWPB-Product	kg CO$_2$-eq.	-0.343	0	0	0	0	0.343	0	
GWPLULUC	kg CO$_2$-eq.	1.12E-04	3.11E-04	9.02E-04	1.84E-05	4.62E-04	2.02E-05	0.00183	±42%
GWPA	kg CO$_2$-eq.	1.44E-07	4.51E-07	2.03E-07	3.37E-08	2.13E-07	2.75E-08	1.07E-06	±57%
ODP	kg R11 eq.	3.22E-16	2.90E-07	2.59E-12	6.11E-13	3.37E-16	7.71E-17	2.90E-07	±50%
AP	kg SO$_2$-eq.	0.00425	0.00356	6.43E-04	3.21E-04	0.00111	1.11E-04	0.0100	±47%
EP	kg PO$_4^{3-}$-eq.	0.00113	8.71E-04	1.18E-04	3.39E-05	4.86E-05	1.46E-05	0.00222	±47%
POFP	kg NMVOC-eq.	0.00536	0.00296	4.52E-04	6.66E-05	2.28E-04	7.47E-05	0.00913	±36%

Table 4-3: Environmental impacts of live mussels, New Zealand distribution (per 1 kg of meat)

Impact indicator	Unit	Farming	Processing	Packaging	Distribution	Distribution Wastage	Use Phase	End-of-Life	Total	CoV
GWPT	kg CO$_2$-eq.	0.796	0.643	1.60	0.0920	0.374	0.106	0.398	4.01	±29%
GWPF	kg CO$_2$-eq.	0.586	0.454	1.60	0.0900	0.258	0.104	0.0577	3.15	±32%
GWPB	kg CO$_2$-eq.	0.553	0.189	0.00512	0.00201	0.116	7.22E-04	-0.00222	0.863	±18%
GWPB-Product	kg CO$_2$-eq.	-0.343	0	0	0	0	0	0.343	0	
GWPLULUC	kg CO$_2$-eq.	1.12E-04	2.88E-04	5.38E-04	2.84E-05	9.54E-05	4.62E-04	4.34E-05	0.00157	±49%
GWPA	kg CO$_2$-eq.	1.44E-07	4.37E-07	1.80E-06	5.21E-08	2.24E-07	2.13E-07	5.92E-08	2.93E-06	±32%
ODP	kg R11 eq.	3.22E-16	2.90E-07	4.82E-15	9.44E-13	2.70E-08	3.37E-16	1.66E-16	3.17E-07	±50%
AP	kg SO$_2$-eq.	0.00425	0.00351	0.00810	4.97E-04	0.00158	0.00111	2.40E-04	0.0193	±34%
EP	kg PO$_4^{3-}$-eq.	0.00113	8.66E-04	7.20E-04	5.25E-05	3.26E-04	4.86E-05	3.14E-05	0.00318	±41%
POFP	kg NMVOC-eq.	0.00536	0.00291	0.00997	1.03E-04	0.00175	2.28E-04	1.61E-04	0.0205	±27%

Table 4-4: Environmental impacts of potted mussels, New Zealand distribution (per 1 kg of meat)

Impact indicator	Unit	Farming	Processing		Distribution	Distribution Wastage	Use Phase	End-of-Life	Total	CoV
GWPT	kg CO_2-eq.	0.796	0.657	0.356	0.0405	0.254	0.106	0.343	2.55	±33%
GWPF	kg CO_2-eq.	0.586	0.469	0.369	0.0396	0.141	0.104	0	1.71	±41%
GWPB	kg CO_2-eq.	0.553	0.187	-0.0127	8.83E-04	0.114	7.22E-04	0	0.843	±16%
GWPB-Product	kg CO_2-eq.	-0.343	0	0	0	0	0	0.343	0	
GWPLULUC	kg CO_2-eq.	1.12E-04	3.34E-04	3.70E-04	1.25E-05	8.26E-05	4.62E-04	0	0.00137	±37%
GWPA	kg CO_2-eq.	1.44E-07	4.65E-07	3.89E-07	2.29E-08	9.25E-08	2.13E-07	0	1.33E-06	±43%
ODP	kg R11 eq.	3.22E-16	2.90E-07	7.03E-13	4.15E-13	2.70E-08	3.37E-16	0	3.17E-07	±0%
AP	kg SO_2-eq.	0.00425	0.00361	0.00364	2.19E-04	0.00114	0.00111	0	0.0140	±37%
EP	kg PO_4^{3-}-eq.	0.00113	8.76E-04	2.27E-04	2.31E-05	2.78E-04	4.86E-05	0	0.00259	±45%
POFP	kg NMVOC-eq.	0.00536	0.00300	0.00170	4.53E-05	9.81E-04	2.28E-04	0	0.0113	±34%

4.1.2. Oysters – Environmental Impact Indicators

The impacts of oysters sold in New Zealand across their full life cycle can be seen in Figure 4-2 and Table 4-5 to Table 4-7. Farming is the most significant stage in terms of GWPT due largely to the carbon dioxide released during shell formation and the diesel usage in both trucks and barges in this stage (see Table 4-9 for more information). The farming stage in Table 4-5, Table 4-6 and Table 4-7 includes the sequestration of carbon in the meat of the oyster, which is not included in the cradle-to-gate value used in section 4.3.2 for the comparison to other protein sources.

The carbon dioxide release during shell formation is counter intuitive due to the fact that there is carbon in the shell (in the form of calcium carbonate). This release occurs because in the chemical reaction to form calcium carbonate, carbon dioxide is a by-product (see section 3.4 and Annex C for more information). The End-of-Life impacts of potted meat are zero apart from the release of biogenic carbon in the meat due to the packaging waste disposal impacts being included in the packaging section and there being no shell to dispose of.

The main difference in carbon footprints between products is from the processing stage, due to the different types of packaging used for each product type. Frozen half shell oysters are modelled as being supplied in PET trays in cardboard boxes, which have low impacts due to the low weight per dozen oysters (see Table 3-14) as well as cardboard being a relatively low-carbon packaging material. Live product is modelled as being supplied on plastic trays inside polystyrene boxes. As live mussels take up more volume than frozen half shell mussels, more packaging per kilogram of product is required.

Furthermore, the product waste rate applied to fresh products (live and potted meat) is relatively large (9.3%) compared to the that assumed for frozen products (0%) – see section 3.2.7. The impact of all of the upstream impacts of wasted product is shown in the “distribution wastage” stage, which follows the principal of modularity, commonly used in LCA.

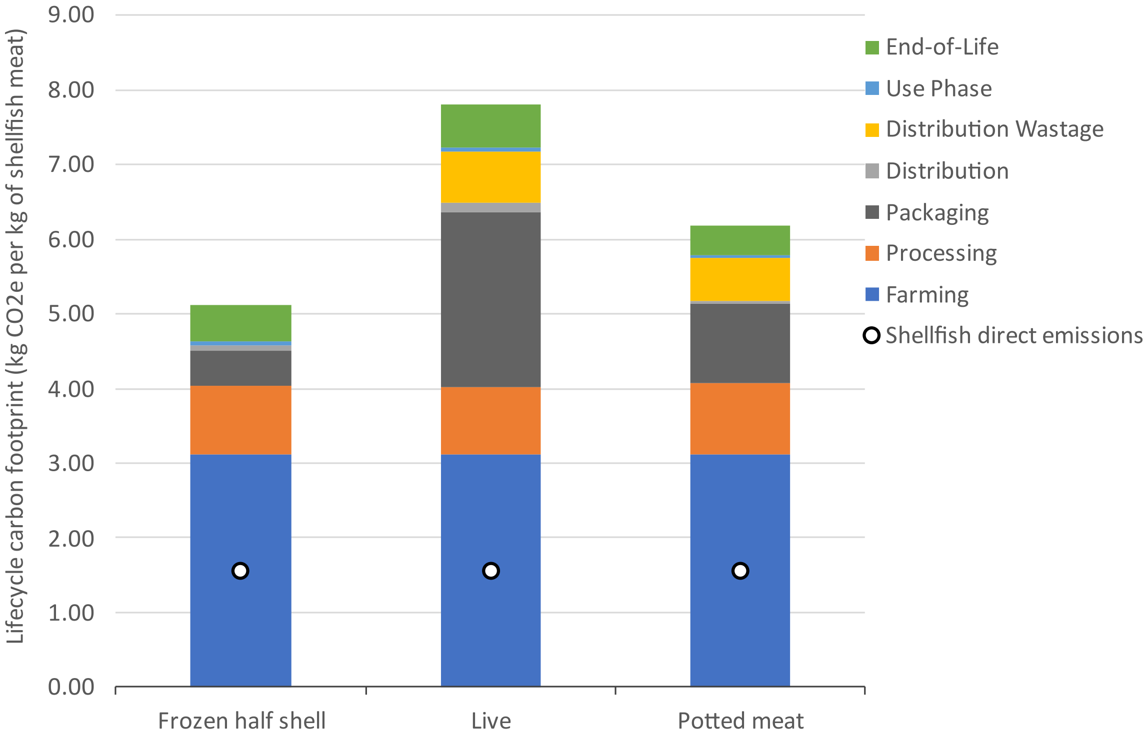

Figure 4-2: Total GWP of oyster products, New Zealand distribution (kg CO_2e per kilogram of meat) Shellfish direct emissions refer mainly to emissions from shell formation

Table 4-5: Environmental impacts of frozen half shell oysters, New Zealand distribution (per 1 kg of meat)

Impact indicator	Unit	Farming	Processing	Packaging	Distribution	Use Phase	End-of-Life	Total	CoV
GWPT	kg CO$_2$-eq.	3.12	0.920	0.467	0.0751	0.0460	0.488	5.11	±33%
GWPF	kg CO$_2$-eq.	2.41	0.853	0.524	0.0726	0.0453	0.0934	3.99	±68%
GWPB	kg CO$_2$-eq.	1.11	0.0663	-0.0583	0.00244	3.34E-04	-0.00359	1.11	±127%
GWPB-Product	kg CO$_2$-eq.	-0.398	0	0	0	0	0.398	0	
GWPLULUC	kg CO$_2$-eq.	0.00107	0.00140	0.00123	3.46E-05	3.45E-04	7.02E-05	0.00414	±45%
GWPA	kg CO$_2$-eq.	9.42E-07	2.38E-06	5.13E-07	6.31E-08	3.55E-09	9.58E-08	4.00E-06	±47%
ODP	kg R11 eq.	2.57E-14	4.60E-08	3.25E-12	1.04E-16	7.16E-18	2.68E-16	4.60E-08	±20%
AP	kg SO$_2$-eq.	0.0159	0.0122	0.00253	6.05E-04	1.22E-04	3.88E-04	0.0318	±58%
EP	kg PO$_4^{3-}$-eq.	0.00286	0.00121	3.58E-04	6.39E-05	2.46E-05	5.08E-05	0.00457	±90%
POFP	kg NMVOC-eq.	0.0126	0.00312	0.00224	1.25E-04	6.80E-05	2.60E-04	0.0184	±92%

Table 4-6: Environmental impacts of live oysters, New Zealand distribution (per 1 kg of meat)

Impact indicator	Unit	Farming	Processing	Packaging	Distribution	Distribution Wastage	Use Phase	End-of-Life	Total	CoV
GWPT	kg CO$_2$-eq.	3.12	0.894	2.34	0.137	0.690	0.0460	0.578	7.81	±28%
GWPF	kg CO$_2$-eq.	2.41	0.824	2.34	0.133	0.534	0.0453	0.187	6.47	±52%
GWPB	kg CO$_2$-eq.	1.11	0.0686	0.00792	0.00446	0.155	3.34E-04	-0.00719	1.34	±85%
GWPB-Product	kg CO$_2$-eq.	-0.398	0	0	0	0	0	0.398	0	
GWPLULUC	kg CO$_2$-eq.	0.00107	0.00132	9.34E-04	6.33E-05	3.20E-04	3.45E-04	1.41E-04	0.00418	±42%
GWPA	kg CO$_2$-eq.	9.42E-07	2.33E-06	3.47E-06	1.16E-07	6.35E-07	3.55E-09	1.92E-07	7.69E-06	±34%
ODP	kg R11 eq.	2.57E-14	4.60E-08	9.63E-15	1.91E-16	4.28E-09	7.16E-18	5.38E-16	5.03E-08	±20%
AP	kg SO$_2$-eq.	0.0159	0.0120	0.0128	0.00111	0.00395	1.22E-04	7.77E-04	0.0467	±48%
EP	kg PO$_4^{3-}$-eq.	0.00286	0.00119	0.00124	1.17E-04	5.71E-04	2.46E-05	1.02E-04	0.00611	±78%
POFP	kg NMVOC-eq.	0.0126	0.00296	0.0159	2.29E-04	0.00299	6.80E-05	5.21E-04	0.0353	±60%

Table 4-7: Environmental impacts of potted oysters, New Zealand distribution (per 1 kg of meat)

Impact indicator	Unit	Farming	Processing	Packaging	Distribution	Distribution Wastage	Use Phase	End-of-Life	Total	CoV
GWPT	kg CO_2-eq.	3.12	0.947	1.08	0.0317	0.568	0.0460	0.398	6.19	±32%
GWPF	kg CO_2-eq.	2.41	0.881	1.08	0.0307	0.413	0.0453	0	4.86	±64%
GWPB	kg CO_2-eq.	1.11	0.0639	0.00236	0.00103	0.154	3.34E-04	0	1.33	±87%
GWPB-Product	kg CO_2-eq.	-0.398	0	0	0	0	0	0.398	0	
GWPLULUC	kg CO_2-eq.	0.00107	0.00148	2.78E-04	1.46E-05	2.70E-04	3.45E-04	0	0.00346	±58%
GWPA	kg CO_2-eq.	9.42E-07	2.43E-06	6.65E-07	2.66E-08	3.76E-07	3.55E-09	0	4.44E-06	±48%
ODP	kg R11 eq.	2.57E-14	4.60E-08	1.62E-15	4.40E-17	4.28E-09	7.16E-18	0	5.03E-08	±20%
AP	kg SO_2-eq.	0.0159	0.0124	0.00884	2.55E-04	0.00353	1.22E-04	0	0.0410	±53%
EP	kg PO_4^{3-}-eq.	0.00286	0.00123	5.78E-04	2.70E-05	5.05E-04	2.46E-05	0	0.00523	±87%
POFP	kg NMVOC-eq.	0.0126	0.00328	0.00967	5.29E-05	0.00242	6.80E-05	0	0.0281	±72%

4.2. Hotspot Analysis

The following section contains a hotspot assessment of the major areas of environmental impact in the lifecycle of live mussels and live oysters distributed within New Zealand. Only live product has been considered under this level of detail because the detailed breakdown is largely similar, aside from the packaging and wastage impacts, which can be seen in section 4.1.

4.2.1. Hotspot Analysis of Mussels

Table 4-8 shows the impacts of all processes in the life cycle of live mussels sold on the domestic market. Processes that contribute ≥10% to the impact are highlighted in red, processes greater than 1% and less than 10% are in black, and processes that contribute ≤1% are in grey. Processes which contribute a 'negative impact' (via the sequestration of carbon) are in green.

Packaging of live products is the single most significant hotspot across all indicators, except for Ozone Depletion Potential. The significance of packaging is lower for frozen half shell products, as less packaging is needed, but it remains important.

For Global Warming Potential Total (GWPT), the most significant stages are packaging, shell formation, denitrification, diesel used for farming, thermal energy used in processing, and product wastage. Cooking is significant in some markets, but it is a relatively small contributor in the domestic market (Table 4-8) due to New Zealand's largely renewable electricity mix. It is important to note that two of these stages (denitrification and shell formation) are naturally occurring processes and outside the control of the mussel industry (see section 3.4 for more information). The cooking stage is also outside the direct control of the industry and is a recommended step in the safe consumption of mussels. The significant stages under industry control are largely due to the packaging choices and fossil fuels combusted.

The carbon in the shellfish meat is considered to be sequestered in the farming stage (hence the negative value) and released at the end-of-life of the mussel, after it has been consumed. This follows ISO 14067 (ISO, 2018), the international standard for carbon footprinting of products. This results in a net zero impact of the carbon in the meat across the lifecycle of the mussel. The sequestration of carbon in the meat is not included in the cradle-to-gate value used in section 4.3.2 for the comparison to other protein sources, which follows ISO 14607.

For Acidification Potential (AP), Eutrophication Potential (EP) and Photochemical Ozone Formation Potential (POFP), the most significant stages are packaging, diesel used in farming, processing thermal energy, and wasted product. The significant contribution to EP from "Farming: Other" is due to the production of cotton socking. The dominant process for Ozone Depletion Potential (ODP) is the R22 refrigerant used by some processors which is modelled as being emitted to air in the processing stage.

Table 4-8: Hotspot analysis for the life cycle of live mussels (NZ distribution)

	Global warming potential (total)	Ozone Depletion Potential	Acidification potential of land and water	Eutrophication potential	Photochemical ozone formation potential
Farming: Electricity	0.0%	0.0%	0.2%	0.0%	0.0%
Farming: Denitrification	**5.3%**	0.0%	0.0%	**5.5%**	0.1%
Farming: Transport to Processing	**2.3%**	0.0%	**1.3%**	**1.4%**	0.5%
Farming: Organic Waste	0.1%	0.0%	0.0%	0.2%	0.0%
Farming: Other	**1.0%**	0.0%	**1.5%**	**10.6%**	**1.3%**
Farming: Ropes + Floats	**2.7%**	0.0%	**3.7%**	**1.4%**	**2.1%**
Farming: Shell Formation CO2	**8.4%**	0.0%	0.0%	0.0%	0.0%
Farming: Thermal Energy	0.2%	0.0%	0.1%	0.0%	0.1%
Farming: Diesel	**8.1%**	0.0%	**15.1%**	**16.4%**	**22.0%**
Farming: Waste	0.0%	0.0%	0.0%	0.0%	0.0%
Farming: Spat	0.1%	0.0%	0.2%	0.2%	0.0%
Farming: Water	0.0%	0.0%	0.0%	0.0%	0.0%
Processing: Electricity	**2.3%**	0.0%	**7.8%**	**1.1%**	**1.2%**
Processing: Forklifts	0.1%	0.0%	0.1%	0.2%	0.2%
Processing: Organic Waste	**4.4%**	0.0%	0.3%	**8.8%**	0.6%
Processing: Other	0.0%	0.0%	0.0%	0.1%	0.0%
Packaging: Packaging	**39.6%**	0.0%	**40.9%**	**20.1%**	**48.1%**
Processing: Refrigerants	**1.6%**	**91.5%**	0.3%	0.4%	0.0%
Processing: Thermal Energy	**6.0%**	0.0%	**8.8%**	**9.4%**	**11.7%**
Processing: Waste	**1.5%**	0.0%	0.7%	**7.2%**	0.5%
Processing: Water	0.2%	0.0%	0.1%	0.2%	0.0%
Distribution: Transport	**1.2%**	0.0%	**1.4%**	**1.5%**	0.3%

	Global warming potential (total)	Ozone Depletion Potential	Acidification potential of land and water	Eutrophication potential	Photochemical ozone formation potential
Distribution: Retail Coldstore	0.3%	0.0%	**1.2%**	0.2%	0.2%
Distribution: R_Refrigerants	0.8%	0.0%	0.0%	0.0%	0.0%
Distribution Wastage: Waste meat sink	**-0.2%**	0.0%	0.0%	0.0%	0.0%
Distribution Wastage: Waste	**1.5%**	**0.0%**	0.3%	**2.1%**	0.2%
Distribution wastage: Wasted product	**8.1%**	**8.5%**	**7.9%**	**8.1%**	**8.3%**
Use Phase: Cooking	**1.5%**	0.0%	**5.1%**	0.8%	0.8%
Use Phase: Retailer to Customer	**1.1%**	0.0%	0.6%	0.8%	0.3%
Packaging: Packaging EoL	0.3%	0.0%	**1.1%**	**2.5%**	0.6%
End-of-Life: Shell Waste	**1.4%**	0.0%	**1.2%**	1.0%	0.8%

4.2.2. Hotspot Analysis of Oysters

Table 4-9 shows the impacts of all processes in the life cycle of live oysters sold in the domestic market. Processes that contribute ≥10% to the impact are highlighted in red, processes greater than 1% and less than 10% are in black, and processes that contribute ≤1% are in grey. Processes which contribute a ‘negative impact’ (via the sequestration of carbon) are in green.

For Global Warming Potential (GWPT), the most significant stages are the barges and trucks used in farming, shell formation, packaging, electricity used in processing, and product wastage. It is important to note that the shell formation is a naturally occurring processes and outside the control of the oyster industry (see section 3.4 for more information).

The carbon in the shellfish meat is sequestered in the farming stage (hence the negative value) and released at the end-of-life of the oyster, after it has been consumed. This follows ISO 14067 (ISO, 2018), the international standard for the carbon footprinting of products. This results in a net zero impact of the carbon in the meat across the lifecycle of the oyster. The sequestration of carbon in the meat is not included in the cradle-to-gate value used in section 4.3.2 for the comparison to other protein sources.

For Acidification Potential (AP), Eutrophication Potential (EP) and Photochemical Ozone Formation Potential (POFP), the most significant stages are diesel used in farming (barges and trucks), packaging, denitrification, electricity used in processing, and product wastage. For EP, the disposal of processing waste is also significant. The dominant process for Ozone Depletion Potential (ODP) is the R22 refrigerant used by some processors which is modelled as being emitted to air in the processing stage.

Table 4-9: Hotspot analysis for the life cycle of live oysters (NZ distribution)

Stage	Global warming potential (total)	Ozone depletion potential	Acidification potential of land and water	Eutrophication potential	Photochemical ozone formation potential
Farming: Cable ties	0.0%	0.0%	0.0%	0.0%	0.0%
Farming: Barges	**17.6%**	0.0%	**17.3%**	**24.3%**	**30.1%**
Farming: Diesel Trucks	**16.3%**	0.0%	**13.4%**	**18.5%**	**6.7%**
Farming: Denitrification	**7.4%**	0.0%	0.0%	**7.2%**	0.1%
Farming: Electricity	0.9%	0.0%	**2.2%**	0.4%	0.5%
Farming: Mesh bags	**1.6%**	0.0%	0.6%	0.5%	0.8%
Farming: Shell CO_2	**18.0%**	0.0%	0.0%	0.0%	0.0%
Farming: Skips	0.5%	0.0%	0.8%	0.3%	0.5%
Farming: Spat	0.9%	0.0%	**2.3%**	0.4%	0.5%
Farming: Trays	0.0%	0.0%	0.1%	0.0%	0.1%
Farming: Waste	0.6%	0.0%	0.3%	0.4%	0.4%
Farming: Wood	**-7.1%**	0.0%	**1.9%**	**2.6%**	**5.2%**
Processing: Diesel	**1.0%**	0.0%	**1.3%**	**1.8%**	**2.7%**
Packaging: Packaging	**17.2%**	0.0%	**21.0%**	**9.3%**	**33.9%**
Processing: Other	**-0.1%**	0.0%	0.2%	0.2%	0.2%
Processing: Electricity	**9.7%**	0.0%	**24.3%**	**4.6%**	**5.7%**
Processing: LPG	0.5%	0.0%	0.1%	0.1%	0.1%
Processing: Pallet	**-0.7%**	0.0%	0.4%	0.5%	0.8%
Processing: Salt	0.0%	0.0%	0.0%	0.0%	0.0%
Processing: Shrink wrap	0.4%	0.0%	0.1%	0.1%	0.2%
Processing: Waste	**4.1%**	0.0%	**1.4%**	**12.6%**	**1.7%**
Processing: Water	0.3%	0.0%	0.1%	0.2%	0.1%

Stage	Global warming potential (total)	Ozone depletion potential	Acidification potential of land and water	Eutrophication potential	Photochemical ozone formation potential
Processing: Refrigerants	0.2%	**91.5%**	**2.3%**	**3.3%**	0.0%
Distribution: Transport	0.4%	0.0%	0.3%	0.5%	0.1%
Distribution: Retail Coldstore NZ	0.1%	0.0%	0.3%	0.1%	0.1%
Distribution wastage: Waste disposal	1.0%	**0.0%**	0.1%	**1.3%**	0.1%
Distribution wastage: Waste meat CO_2	**-0.2%**	0.0%	0.0%	0.0%	0.0%
Distribution wastage: Wasted product	**8.4%**	**8.5%**	**8.5%**	**8.4%**	**8.5%**
Use Phase: Retailer to Customer	0.7%	0.0%	0.3%	0.5%	0.2%
End-of-Life: Shell Waste	0.0%	0.0%	0.0%	0.0%	0.0%
Packaging: Packaging EOL	0.2%	0.0%	0.6%	**1.7%**	0.5%

4.3. Results per 100 Grams of Protein

4.3.1. Comparison to Other Protein Sources (Cradle-to-Retail)

The results from this study have been compared to another study by Poore and Nemecek (2018) that consolidated data on the environmental impacts of various types of food production systems, covering 40 agricultural products. In doing this, the study created global production averages for a variety of food products.

Figure 4-3 compares the average (mean) carbon footprint of the products considered to be ‘high protein’ by Poore and Nemecek to the results of this study per 100 grams of protein.

Bars are used to show the 10th and 90th percentiles provided by Poore & Nemecek which give an indication of the range of results within a particular protein source, due to different production methods, technologies, and location. It should be noted that the 90th percentile value of beef from beef herds extends to 105 kg CO_2e, which was cut off from the graph in order to not compress the rest of the data. The values seen in Figure 4-3 can also be seen in Table 4-10. The bars shown in the oysters and mussels data show the calculated 10th and 90th percentiles of farmer and processor data for this study.

For all products, the life cycle stages considered spans from “cradle-to-retail” which includes the inputs through to the point of retail (i.e., farming, processing, distribution, and distribution loss if applicable) as this is the system boundary used by Poore and Nemecek. Where applicable, Poore and Nemecek consider studies which only use economic allocation (or studies that can be adjusted to economic allocation) to split production impacts between co-products. Economic allocation is not used in this study as it has been determined that there are no valuable co-products. In effect, this is the same as what was done by Poore and Nemecek as when the economic value of a co-product is zero, it is not allocated any of the upstream burdens.

Shellfish have a higher carbon footprint than all of the non-animal products considered as a source of protein. The only exception is for tofu where frozen half shell mussels have a slightly lower carbon footprint. Frozen half shell mussels, frozen half shell oysters, and potted mussels have a lower carbon footprint than all animal proteins considered by Poore and Nemecek. Potted oysters and live mussels have a smaller carbon footprint than all animal protein considered by Poore and Nemecek except for eggs. Live oysters have a similar carbon footprint to poultry meat.

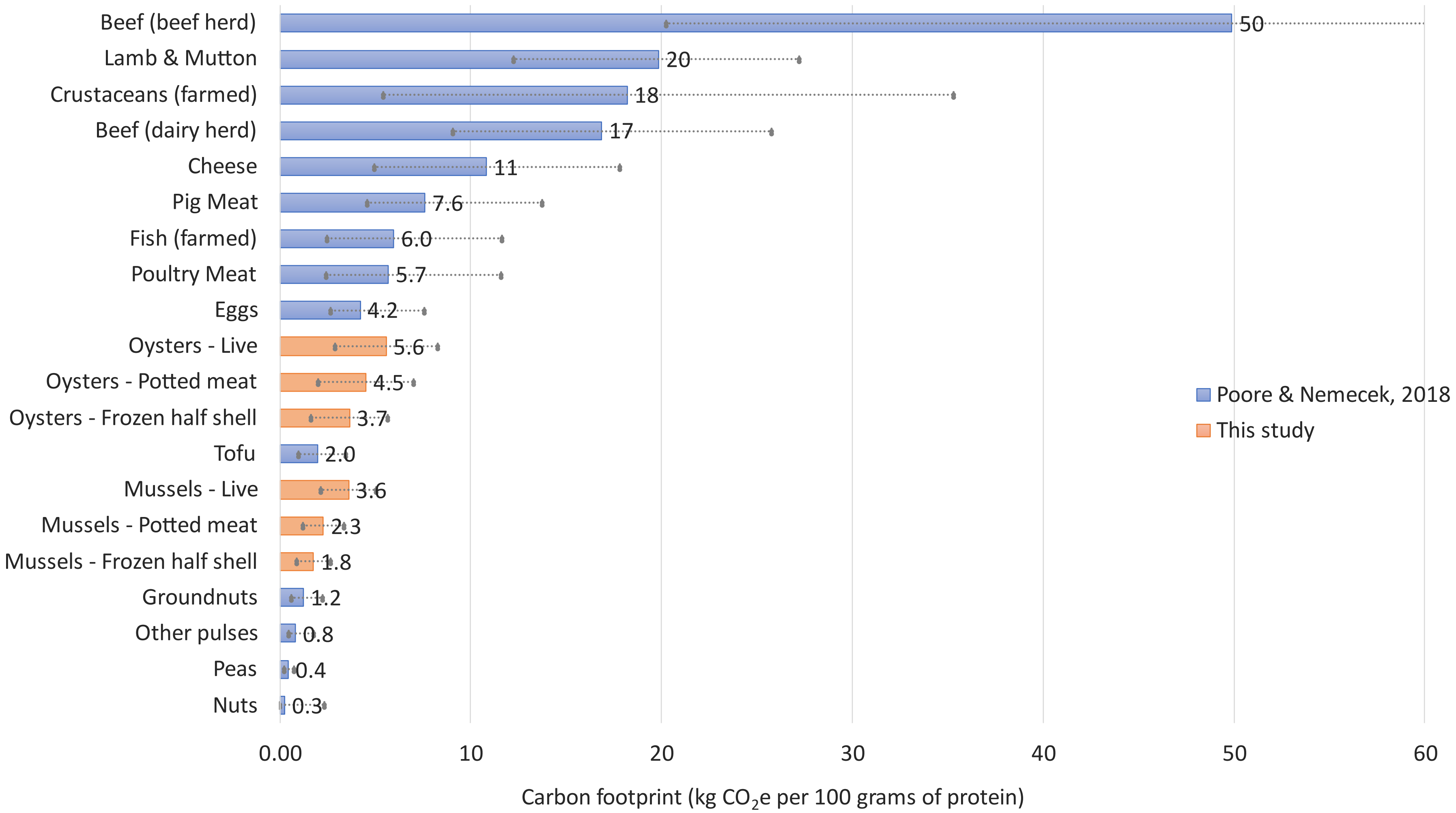

Figure 4-3: Carbon footprint of protein sources (cradle-to-retail) (kg CO$_2$e per 100 grams of protein) (Poore & Nemecek, 2018)

Table 4-10: Carbon footprint of protein sources (cradle-to-retail) (kg CO_2e per 100 grams of protein) (Poore & Nemecek, 2018)

Stage	Mean	10th Percentile	90th Percentile
Nuts	0.263	-2.24	2.35
Peas	0.441	0.252	0.75
Other pulses	0.836	0.458	1.75
Groundnuts	1.23	0.623	2.22
Mussels - Frozen half shell	1.76	0.87	2.66
Mussels - Potted meat	2.29	1.20	3.38
Mussels - Live	3.60	2.16	5.04
Tofu	1.98	1.00	3.47
Oysters - Frozen half shell	3.66	1.65	5.67
Oysters - Potted meat	4.52	2.01	7.03
Oysters - Live	5.57	2.88	8.27
Eggs	4.21	2.64	7.56
Poultry Meat	5.70	2.41	11.6
Fish (farmed)	5.98	2.48	11.6
Pig Meat	7.61	4.58	13.8
Cheese	10.8	4.95	17.8
Beef (dairy herd)	16.9	9.09	25.8
Crustaceans (farmed)	18.2	5.44	35.3
Lamb & Mutton	19.9	12.3	27.2
Beef (beef herd)	49.9	20.2	105

4.3.2. Comparison to Published LCAs of Shellfish (Cradle-to-Gate)

This study was also compared to international shellfish LCAs published in various journals. Due to significant differences in methodology and functional units, it can be difficult to make fair comparisons with other studies and care should be taken whenever doing so. The key methodological differences encountered in the analysis of other studies are:

- The inclusion of capital goods (e.g., the manufacturing of barges used in farming) in the study. This study did not include capital goods, which is common practice in LCA studies. Of the shellfish LCAs considered in this section, Iribarren et al. (2009) and Lourguioui et al. (2017) included capital goods. These impacts were notable (~20% for GWP in Lourguioui and stated as a major contributor by Iribarren.
- Interactions with the environment by shellfish during growth:
    - Significantly (from a carbon footprint perspective), most other studies have not included the formation of carbon dioxide which occurs as a by-product of shell formation (see Annex C). This results in these studies having a lower carbon footprint than what they would have had if this were included.
    - Some studies (Aubin, et al., 2017) (SARF, 2012) included the sequestration of carbon dioxide during shell formation. In the case of the SARF (Scottish Aquaculture Research Forum) study, the sequestration due to shell formation has been removed from the LCA results in the Figure 4-4.

Figure 4-4 shows the carbon footprint of various other cradle-to-gate LCA studies, compared to the values found in this study for frozen half shell mussels and oysters. All data has been shown as a carbon footprint per 100g of protein, with some studies needing to be converted by the authors of this study from shellfish weight to protein. When they were not present in the relevant study, the meat-to-shell ratio and protein content used in this calculation were kept the same as those used for the calculation of the protein content in this study (see section 2.2). The interquartile range of the carbon footprint of different molluscs has been taken from the Seafood Carbon Emissions Tool (Dalhousie University, 2018) and provides a range of impacts between which most of the studies considered fall between, as seen by the red and grey lines in Figure 4-4.

The studies included in Figure 4-4 are: (Iribarren, et al., 2009) (Tamburini, et al., 2020) (Frosell, 2019) (SARF, 2012) (Lourguioui, et al., 2017) (Pucylowski, 2017) (de Alvarenga, et al., 2012) (Dalhousie University, 2018)

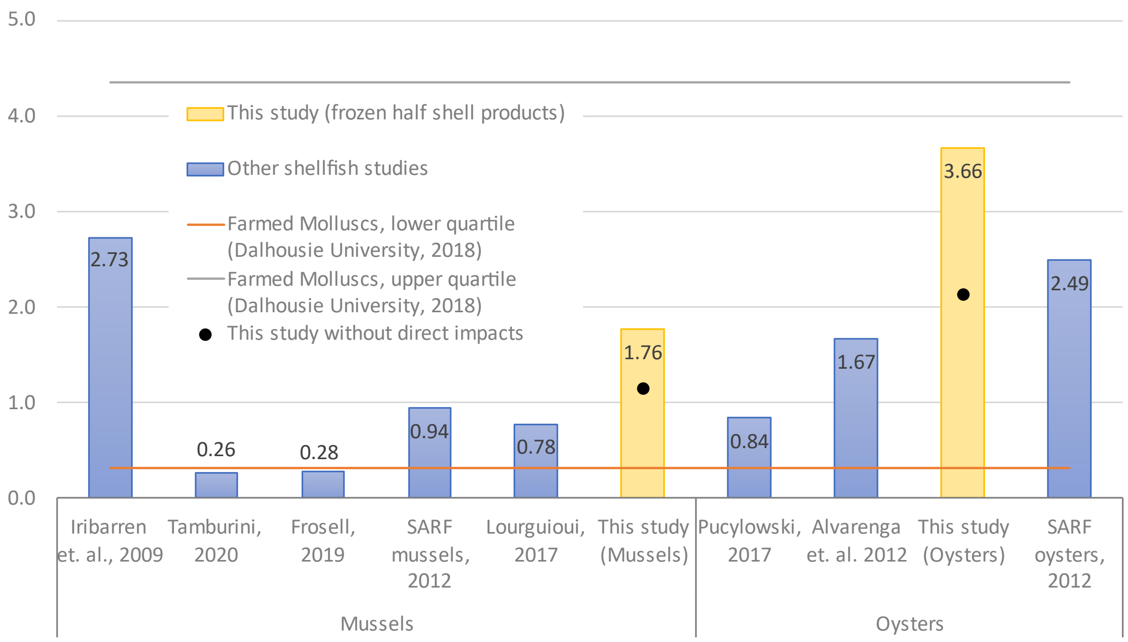

Figure 4-4: Carbon footprint of oyster and mussel studies (cradle-to-gate) (kg CO_2e per 100g of protein)

The other shellfish studies shown in Figure 4-4 do not account for the direct release of greenhouse gases during shellfish growth (see section 3.4), which results in lower values than if these processes were to be included. The paper used by this study to calculate the release of carbon dioxide (Ray, et al., 2018) was released after most of the included studies had been published. The carbon footprint of frozen half shell products from this study without the emissions from the direct release of gases can be seen as a black dot in Figure 4-4. This is a more comparable value to other studies and New Zealand farmed mussels and oysters then sit within the range of the other LCAs.

Figure 4-4 shows a wide range of values, which reflects not only the range in methodology and system boundaries exhibited across different studies but also the wide range of different methods and transportation distances involved with the production of these shellfish between the different studies. Farming methods with differing levels of involvement from farmers and differing transportation distances lead to significant differences in fossil fuels used (among other differences) and thus a range of carbon footprints.

It is important to note that while there appears to be a significant range in the carbon footprint of shellfish in relative terms (i.e. there is a factor of 10 difference between (Iribarren, et al., 2009) and (Tamburini, et al., 2020)), this range is relatively small in absolute terms (less than 3 kg CO_2e / 100 g protein). Even the highest value in Figure 4-4, (the upper quartile value of molluscs from the Seafood Carbon Emissions Tool (Dalhousie University, 2018)) is lower than the mean of all other animal proteins considered by Poore & Nemecek (2018), except for eggs (4.4 kg CO_2e / 100 g protein).

4.4. Transportation Variation

This section considers the carbon footprint of transporting frozen half shell products and live products to international markets. Potted meat is not considered as it is not a product which is generally exported.

4.4.1. Frozen Half Shell Products

Figure 4-5 shows the differences between the distribution scenarios shown in sections 3.2.7 and 3.3.6 for one kilogram of meat from frozen half shell mussels and oysters. As these products are shipped in large, refrigerated container ships which are able to transport massive volumes of goods at once, the distribution impacts are minor and do not have a significant impact over the lifecycle of the product. The average, minimum, and maximum distances for mussels are approximately equivalent to transport to Los Angeles, Sydney, and Moscow, respectively. The average, minimum, and maximum distances for oysters are approximately equivalent to transport to Perth, Sydney, and Copenhagen, respectively.

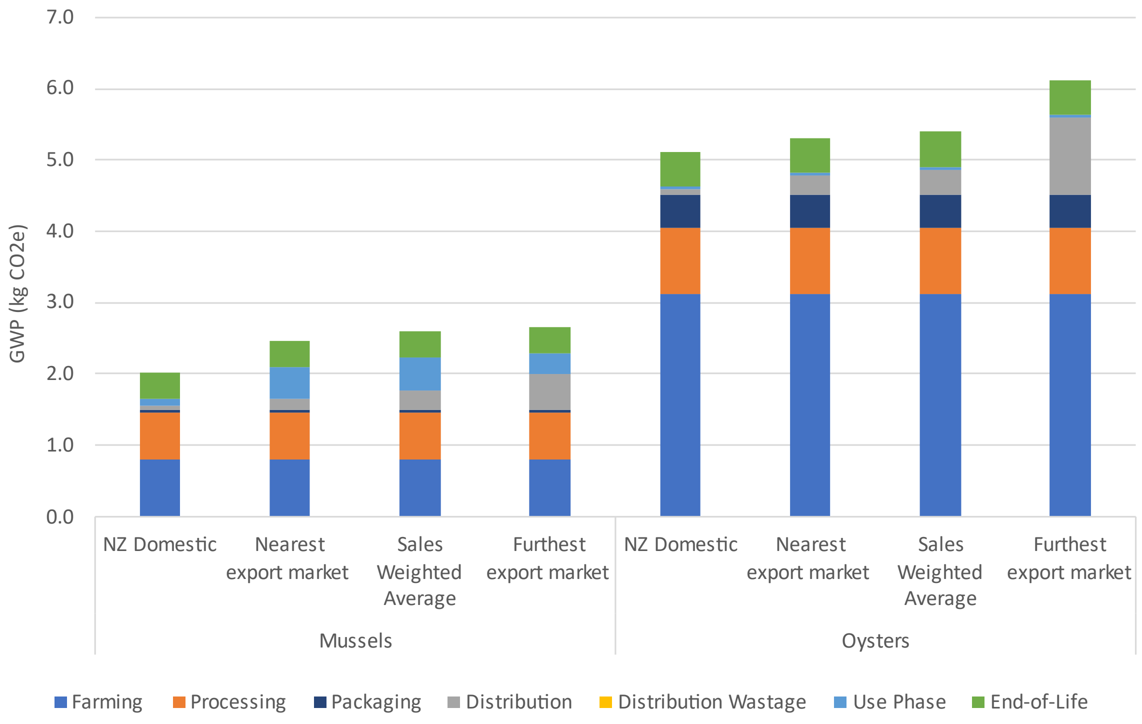

Figure 4-5: Full life cycle carbon footprint of frozen half shell mussels and oysters (per 1 kg of meat)

4.4.2. Live Products

Figure 4-5 shows the differences between the distribution scenarios shown in sections 3.2.7 and 3.3.6 for one kilogram of meat from live mussels and oysters. When live product is exported, it is distributed using air freight, which has a high emission factor and so the distribution impacts are significant with respect to the rest of the life cycle. Live products also contain more shell and packaging than half shell products, which means that there is more mass to be distributed. This is especially true in the case of oysters, where approximately 5 kilograms of live oysters are needed for one kilogram of edible meat.

The average, nearest, and furthest export market distances for mussels are approximately equivalent to transport to Beijing, French Polynesia, and Los Angeles, respectively. The average, nearest, and furthest export market distances for oysters are approximately equivalent to transport to Shanghai, Sydney, and Moscow respectively.

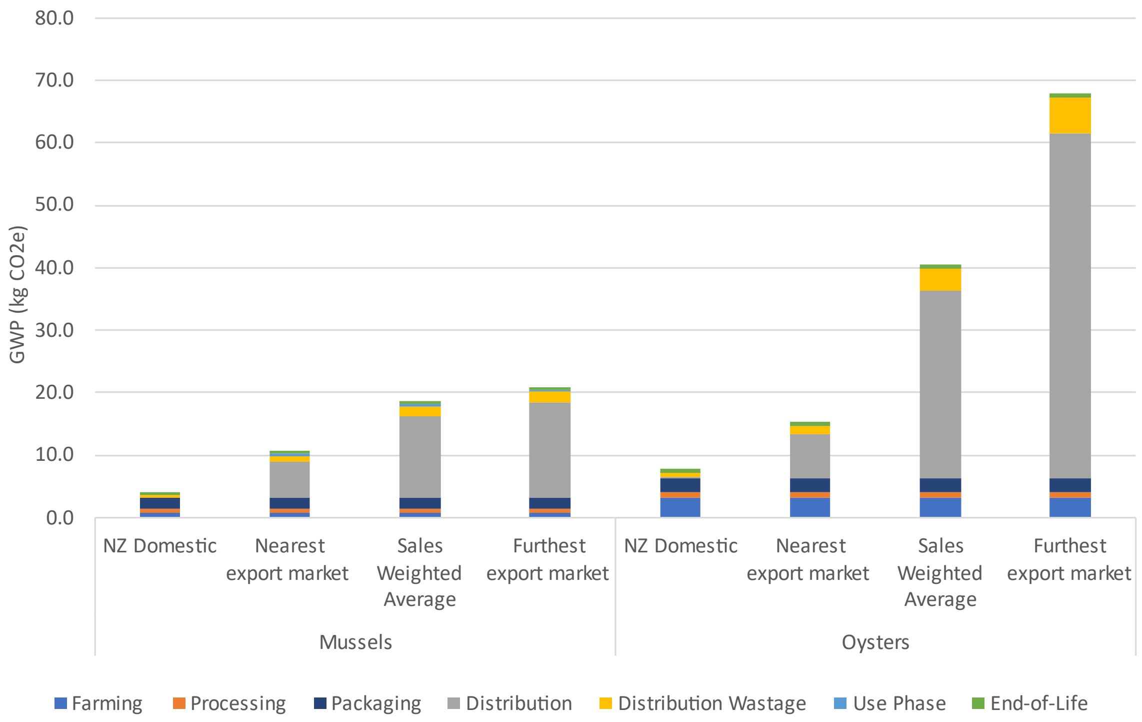

Figure 4-6: Full life cycle carbon footprint of frozen half shell mussels and oysters (per 1 kg of meat)

4.5. Sensitivity Analysis

4.5.1. Variations in Protein Content

The protein content of both mussels and oysters varies both seasonally and regionally. This can have a significant effect on the results as a lower protein content requires more shellfish to be produced in order to get to the comparison unit of 100 grams of protein. Variations in protein content have been obtained by using previous studies of Greenshell Mussels and Pacific Oysters from New Zealand (MacDonald & Hall, 2000) (Ren, et al., 2003). These are older studies than the FOODFiles database values (New Zealand Institute for Plant and Food Research, 2018) which were used in the main analysis. The FOODFiles database is run on behalf of the New Zealand Government and has been updated every couple of years since the 1980s. It is considered the best nutritional information available for these products.

Table 4-11: Protein content variations in shellfish

Shellfish	Main analysis	Minimum protein content	Maximum protein content	Protein range source
Pacific Oyster	13.6%	8.7%	13.7%	(Ren, et al., 2003)
Greenshell Mussel	10.7%	9.0%	16.5%	(MacDonald & Hall, 2000)

The results of this analysis can be seen in Figure 4-7, with the bars showing the range of results from the protein variation. Other protein sources from Poore and Nemecek (2018) that have a similar carbon footprint to shellfish are included in the graph, with their bars indicating the 10th and 90th percentiles of these systems, not due to variations in protein content. In this chart, the highest shellfish carbon footprint is the scenario with the minimum protein content and the lowest shellfish carbon footprint is the scenario with the maximum protein content.

As can be seen in Figure 4-7, the oyster carbon footprint increases significantly under the minimum protein scenario, due to the protein content of oysters in this scenario being significantly lower than the main analysis. This is most likely due to the seasonal variation in the protein content of the gonad. The mussel protein content variation also affects the results, although not to the same degree as the oysters, due to mussels having a higher meat to shell ratio than oysters.

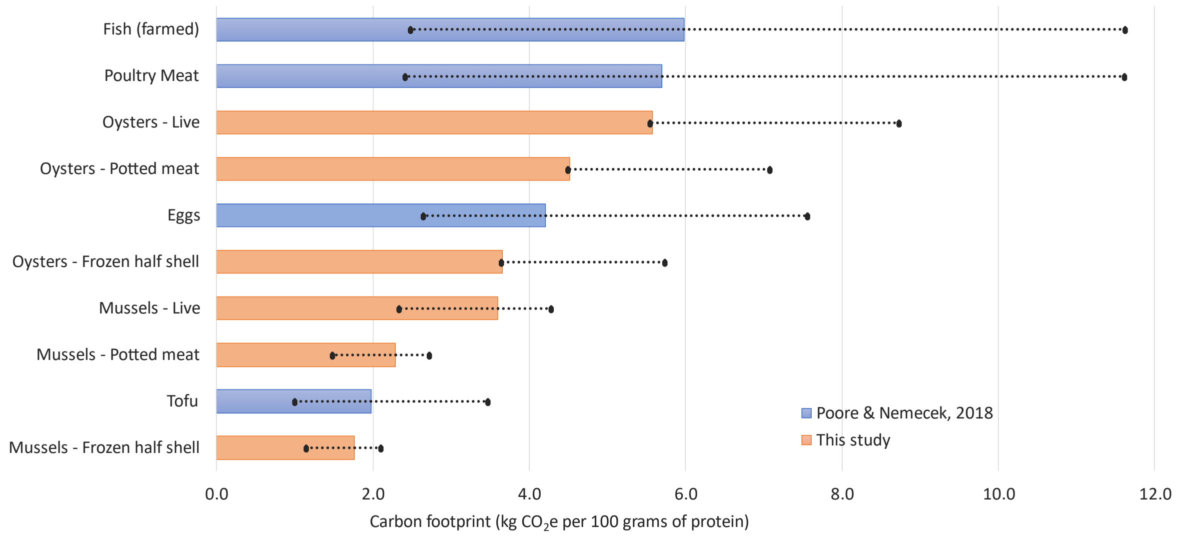

Figure 4-7: Results of protein content variation. Poore & Nemecek range bars show the 10th and 90th percentiles.

4.5.2. GWP 20 Indicator

The twenty-year GWP (GWP 20) indicator was used as a sensitivity analysis in order to understand the impact of short-term gases like methane. GWP 20 gives these short-term gases a higher weighting than the GWP 100 indicator as over a 100-year timescale these gases break down and are no longer in the atmosphere. From Figure 4-8, it can be seen that using the GWP 20 indicator increases the GWP of oyster products by approximately 15-16%, while the GWP of mussel products increases by between 23-30%, depending on the product. Other sources of animal protein will also have significant percentages of their GWP originating from the release of short-lived gases and so their GWP would also increase.

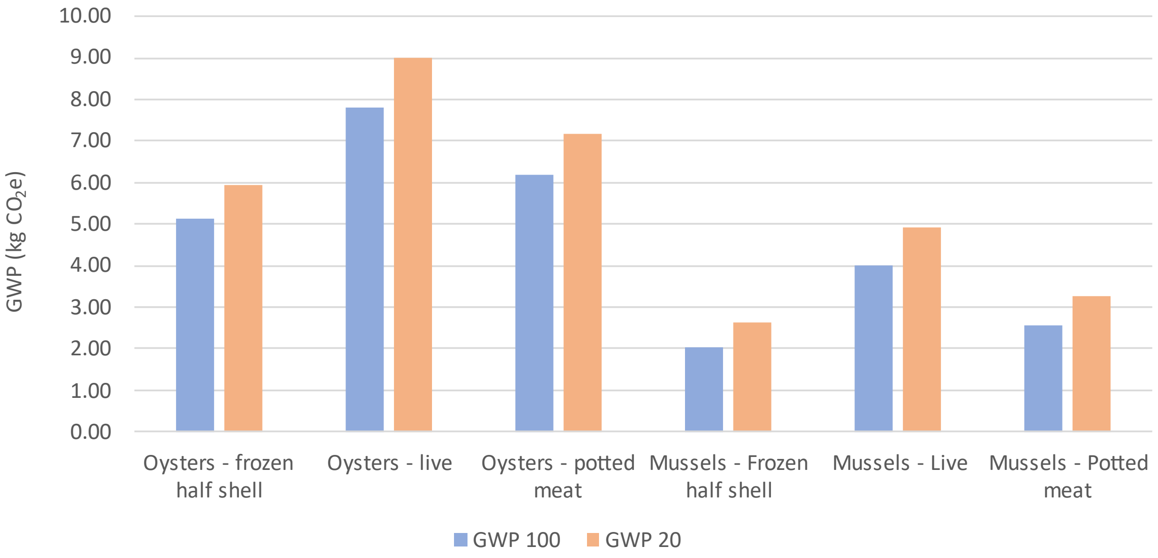

Figure 4-8: Life cycle carbon footprint of domestic shellfish (per 1 kg of meat)

5. Interpretation

5.1. Main Findings

- The diesel used in barges and trucks and the packaging are the areas with the most significant impact on the carbon footprint of mussel and oyster production from “cradle to gate”. Therefore, optimising the use of diesel in transport and the choice of packaging materials are areas with potential for improvement. The release of carbon dioxide during shell formation also has a significant impact, though it is outside the control of mussel and oyster farmers.
- The mode of transport of food products matters significantly more than the distance travelled when considering the carbon footprint of a product. This is shown by the distribution impacts for exported frozen mussels and frozen oysters being low compared to the impacts across the rest of the life cycle as they are shipped using sea freight (see section 4.4.1). However, distribution impacts are highly relevant for live products as they are shipped using air freight, which has a much higher impact per kilometre travelled. This is reflected by the distribution impacts of live exported shellfish being a significant proportion of the life cycle impacts (see section 4.4.2).
- Mussels and oysters have a lower carbon footprint per 100g of protein compared to most other animal products. Even assuming the lowest protein content in shellfish (and therefore the highest impact per 100 grams of protein), only live and potted oysters are comparable to the poultry meat and fish carbon footprint per 100 grams of protein found in Poore & Nemecek (2018).
- There is considerable variation in the carbon footprint of mussels and oysters across different LCA studies. This is due to a range of factors, including differences in farming practices, transport distances and also modelling methodologies applied.
- There are still some old-style refrigerants being used in the New Zealand shellfish industry. These will soon be phased out following the Montreal Protocol.

5.2. Assumptions and Limitations

The main assumptions used in the modelling for this study and the datasets used are described in detail in section 3. Areas where the data used were of lower quality or where significant assumptions had to be made were:

- Capital goods (including the vehicles and buildings) used in the farming and processing of shellfish have not been included in this study. This is a common exclusion amongst the studies considered in section 4.3.2.
- The nitrogen and carbon dioxide cycles have been modelled to include all possible interactions and provide a baseline scenario of the direct impacts caused by farmed shellfish. The pathways modelled are complex and dependant on many localised variables (ocean temperature, oxygen content, etc.), so assumptions have been made to show the potential impact that farmed shellfish have on these cycles.
- The data from the mussel and oyster farmer and processors collected is representative of the wider New Zealand industry. It is estimated that between 50 and 70 percent of the mussel and oyster industry in New Zealand was included in this study.

- Differing distribution scenarios (domestic, sales weighted export, etc) has a significant impact on the results. Domestic distribution is the baseline scenario used in this report, due to it being compatible with the Poore and Nemecek study.
- It has been assumed that there is no difference between the protein content of frozen and live shellfish of the same species.

5.3. Potential Changes in the Policy Landscape in New Zealand

5.3.1. Thermal Energy

In April 2021, the New Zealand Government proposed banning new coal boilers starting from the end of 2021 and the complete phasing out of coal boilers by 2037 (New Zealand Government, 2021a). None of the shellfish processors who provided data use coal for process heat or any other use; instead, either diesel or natural gas were used. Further study may be required to determine if any shellfish processors associated with Aquaculture New Zealand use coal, but the data collected so far indicates that no changes are needed to meet these regulations.

Further regulations on fossil fuels are likely and given that the cost of these fuels may rise, it would be prudent for shellfish processors to start looking elsewhere for sources of process heat. Electrical heat pumps can in some cases reach the temperatures required by processors and biofuels are another option for boilers, especially for mussel processors who are located near to sources of biomass.

5.3.2. Plastics in Aquaculture

Plastics are used in the life cycle of shellfish for a wide variety of applications, including for mussel ropes, buoys, oyster flip cages, trays, and packaging. The industry acknowledges that this is an area of concern and work is being done to reduce the use of plastics where possible and to increase recycling rates where plastic is necessary. The Ministry for Primary Industries (MPI) published a report by the Sustainable Business Network (SBN) in 2020 covering the use of plastics in aquaculture (Sustainable Business Network, 2020). This report included an industry-wide workshop where potential solutions to plastic waste were assessed based on their impact and viability and allows for future collaboration to improve New Zealand aquaculture as a whole.

5.4. Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistent background LCA information from the GaBi 2020 database were used. The LCI datasets from the GaBi 2020 database are widely distributed and used with the GaBi 10 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

5.4.1. Precision and Completeness

- ✓ **Precision:** As the majority of the relevant foreground data are measured data or calculated based on primary information sources of the owner of the technology, precision is considered to be high. Seasonal variations were balanced out by using yearly averages. Variations across different farmers and processors were balanced out by using weighted averages. All background data are sourced from GaBi databases with the documented precision.

- ✓ **Completeness:** Each foreground process was checked for mass balance and completeness of the emission inventory. No data were knowingly omitted. Completeness of foreground unit process data is considered to be high. All background data are sourced from GaBi Databases with the documented completeness.

5.4.2. Consistency and Reproducibility

- ✓ **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail, while all background data were sourced from the GaBi Databases.
- ✓ **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modelling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modelling approaches.

5.4.3. Representativeness

- ✓ **Temporal:** All primary data were collected for the calendar year 2019 or for the period October 2018 to September 2019 (commonly used as the financial year by New Zealand aquaculture companies). All secondary data come from the GaBi 2020 Databases and are representative of the years 2016-2019. As the study intended to compare the product systems for the reference year 2019, temporal representativeness is considered to be high.
- ✓ **Geographical:** All primary and secondary data were collected specific to the countries or regions under study. Where country-specific or region-specific data were unavailable, proxy data were used. Geographical representativeness is considered to be high.
- ✓ **Technological:** All primary and secondary data were modelled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used. Technological representativeness is considered to be high.

5.5. Model Completeness and Consistency

5.5.1. Completeness

All relevant process steps for each product system were considered and modelled to represent each specific situation. The process chain is considered sufficiently complete and detailed with regards to the goal and scope of this study.

5.5.2. Consistency

All assumptions, methods and data are consistent with each other and with the study’s goal and scope. Differences in background data quality were minimised by exclusively using LCI data from the GaBi 2020 Databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

5.6. Conclusions, Limitations, and Recommendations

5.6.1. Conclusions

The results of this study show that shellfish farmed and processed in New Zealand are one of the lowest carbon footprint sources of animal protein that can be consumed. Significant areas of impact from a carbon footprint perspective are the fuels used by transportation vehicles (trucks, barges, etc.) throughout the production of shellfish, the packaging, product wastage in the retail distribution chain, and the carbon released during shell formation.

Following a Data Quality Assessment, the data used has been deemed to be of sufficient quality and representative of the mussel and oyster industries in New Zealand in 2019. Where assumptions have been required, they have been justified in the Life Cycle Inventory (section 3) and the most significant assumptions have been discussed in section 5.2. These data, as well as the modelling used, provide results which can stand up to critical review and be used to make comparative claims about shellfish relative to other protein sources.

In the current social and political environment, climate change is a major issue that consumers are increasingly considering when it comes to their food choices. This study shows that shellfish should be the animal protein of choice for the climate-conscious consumer. Frozen half shell products are particularly low impact for both domestic and export markets. Air freight of shellfish should be avoided where possible and, where used, closer markets have the lowest impacts.

5.6.2. Limitations

- While mussels and oysters are shown to have a lower carbon footprint than the average (mean) of all animal products studied in Poore and Nemecek (2018), this does not mean that all mussels and oyster products have a lower carbon footprint than the animal proteins studied as there can be significant variation within a single animal product.
- This study is specific to the shellfish farming and processing techniques and technology available in New Zealand in 2019 and is not necessarily transferrable to other markets.
- The GWP_{100} indicator used (from the IPCC's Fifth Assessment Report) looks at Global Warming Potential across a 100-year timeframe, as required by ISO 14067:2018 as a base case (ISO, 2018). Considering shorter or longer-term timeframes may yield different results. This has been considered in section 4.5.2.

5.6.3. Recommendations

- Reducing vehicle fuel use in the farming and processing stages, by identifying and reducing inefficiencies in the supply chain. This would also provide economic benefits to the industry, especially if fuel prices are set to rise in the future.
- Transitioning to renewable fuels for vehicles in the farming and processing stages (in barges and trucks in particular). It is acknowledged that this may be difficult for smaller producers due to the long lifespan of vehicles and their high capital cost. Biodiesel is a low capital-intensive option to reduce emissions, but supply and cost can make it unfeasible at present.
- Reducing the amount of packaging used and/or using reusable packaging (while making sure that systems are in place for the packaging to be used again).

- Switching from burning fossil fuels for thermal energy in processing facilities to low-carbon renewable energy sources, such as biomass or electric boilers.
- Considering what happens to the shell waste mussel and oyster farmers are disposing. These shells have several potential uses such as being included in chicken grit, the creation of reefs, or as a replacement for limestone (due to the high calcium carbonate content). This will also have the benefit of avoiding sending waste to landfills.
- Further analysis of plastic use in the industry, especially for materials that are in contact with the ocean and are likely to release microplastics as they break down.
- Further analysis of the effects of shellfish aquaculture on the nitrogen cycle in New Zealand coastal waters.
- Some refrigerants used by companies in this study have high GWP factors as well as being a significant contributor to ozone depletion (in the case of R22). These will need to be phased to stay in line with the Montreal Protocol, but further work should be done to eliminate the use of all refrigerants which have high Global Warming Potentials.
- Encouraging air cargo operators to explore low-carbon fuel alternatives as the air transportation of live shellfish significantly increases the carbon footprint of these products.
- Increasing the share of the domestic and regional live product market relative to more distant markets, as the impacts of air freighting live product over long distances is significant.
- Some seafood (lobster) has been exported live via sea freight in specialised containers, which according to another study had half the carbon footprint of live lobster distributed via air freight (Borthwick, 2019). This is an option which could be explored for shellfish, but it should be noted that live container-ship lobster still has double the carbon footprint of frozen lobster.
- To continue monitoring the carbon footprint of shellfish, Aquaculture New Zealand could encourage farmers and processors to provide them with fuel and electricity data. This would allow them to have the most up to date (albeit approximate) data to track industry progress. This is already done by some farmers in the AQNZ A+ Sustainable Management Framework (Aquaculture NZ, 2020b). Adding data entry for processors, including their use of packaging, would make future work significantly easier and allow progress to be tracked over time.

To better understand the life cycle impacts of mussels and oysters, future studies can focus on:

- The differences between the impacts of various spat collection methods for oysters and mussels. This is particularly relevant as hatchery spat farming becomes more common for both oysters and mussels.
- The dissolution rate of shells (calcium carbonate) in high-acidity environments in New Zealand coastal waters, especially the Firth of Thames (see Annex D).
- The denitrification process that occurs either in or around bivalves (as described in Annex E). This study bases its numbers on a paper which sparked debate in Europe and better understanding the true significance of this process on the carbon footprint of shellfish would be useful. As this study is conservative in including this process, further research may help to reduce the carbon footprint of shellfish.
- Understanding the differences in impacts of farming methods. As noted in this study, this is difficult as the same farmer may use multiple methods at one point in time and inputs may vary for reasons other than the farming method.

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Annex A Critical Review Report

Annex B Mussel Powder and Oil Results

The results for the production of one kilogram of mussel powder (not including the packaging) can be seen in Table 6-1. As the underlying data is confidential, a detailed split is not able to be shown. The hotspots of the results are the combustion of LPG and the production of the mussels themselves. These results are high level and are indicative as a full LCA has not been carried out. The data associated with these results have been reviewed by the critical review panel.

Table 6-1: Mussel powder results

Impact indicator	Unit	Mussel Powder
GWPT	kg CO_2-eq.	32.0
GWPF	kg CO_2-eq.	23.7
GWPB	kg CO_2-eq.	8.27
GWPLULUC	kg CO_2-eq.	0.0387
GWPA	kg CO_2-eq.	3.36E-06
ODP	kg R11 eq.	8.18E-15
AP	kg SO_2-eq.	0.102
EP	kg PO_4^{3-}-eq.	0.0268
POFP	kg NMVOC-eq.	0.132

No data for mussel oil production could be sourced from suppliers for this project, as the manufacturing process is commercially sensitive and there are a small number of suppliers. Mussel oil is produced by extracting the oils from mussel powder, using solvents (New Zealand Government, 2021b).

It is expected that the environmental impacts of mussel oil will be notably higher than that of powder. Assuming that:

- Mussel oil has a fat content of >99% (Waitaki Biosciences, 2019) (assumed 100%)
- Raw mussel flesh is 1.8% fat by mass (New Zealand Institute for Plant and Food Research, 2018).
- The meat content of mussels is: 51.3% (Miller & Tian, 2017).

Then a minimum of 114 kilograms of greenshell mussels would be required to produce 1 kilogram of mussel oil. Calculation: $Mass = \frac{1}{1.8\% * 0.487} = 114\ kg\ mussels\ (including\ shell)$

The lower limit stated here assumes full extraction of the oil, which may not be possible in a real manufacturing process. This means that it is expected that over 114 kilograms of mussels are required to produce 1 kilogram of oil.

Annex C Interactions with the Carbon Cycle

Background

The LCIA (Life Cycle Impact Assessment) results show that shell formation is a process in the farming stage across both species in which carbon dioxide is generated, and there are some misconceptions in both industry and literature about whether shells sequester carbon or not. Ensuring this is communicated effectively is important for both stakeholders and readers of the study, and this section will use first principles to explain why shell formation is a net source of CO_2 rather than a sink.

The global carbon cycle has traditionally been regulated by interactions between atmospheric, oceanic, and terrestrial systems, with anthropogenic carbon dioxide emissions since the Industrial Revolution upending these balances (Ciais, et al., 2014). Most of the global carbon balance is contained in the ocean (shown in Figure 6-1) where it primarily exists as Dissolved Inorganic Carbon (DIC). This is the total of aqueous CO_2, bicarbonate and carbonate ions which are in constant flux with each other and is distinct from Dissolved Organic Carbon. Three mechanisms are responsible for carbon movement within the oceanic system: the biological pump (where carbon is exchanged via photosynthesis and respiration), the solubility pump (where CO_2 dissolved into its species) and the carbonate pump, which is the focus of this section.

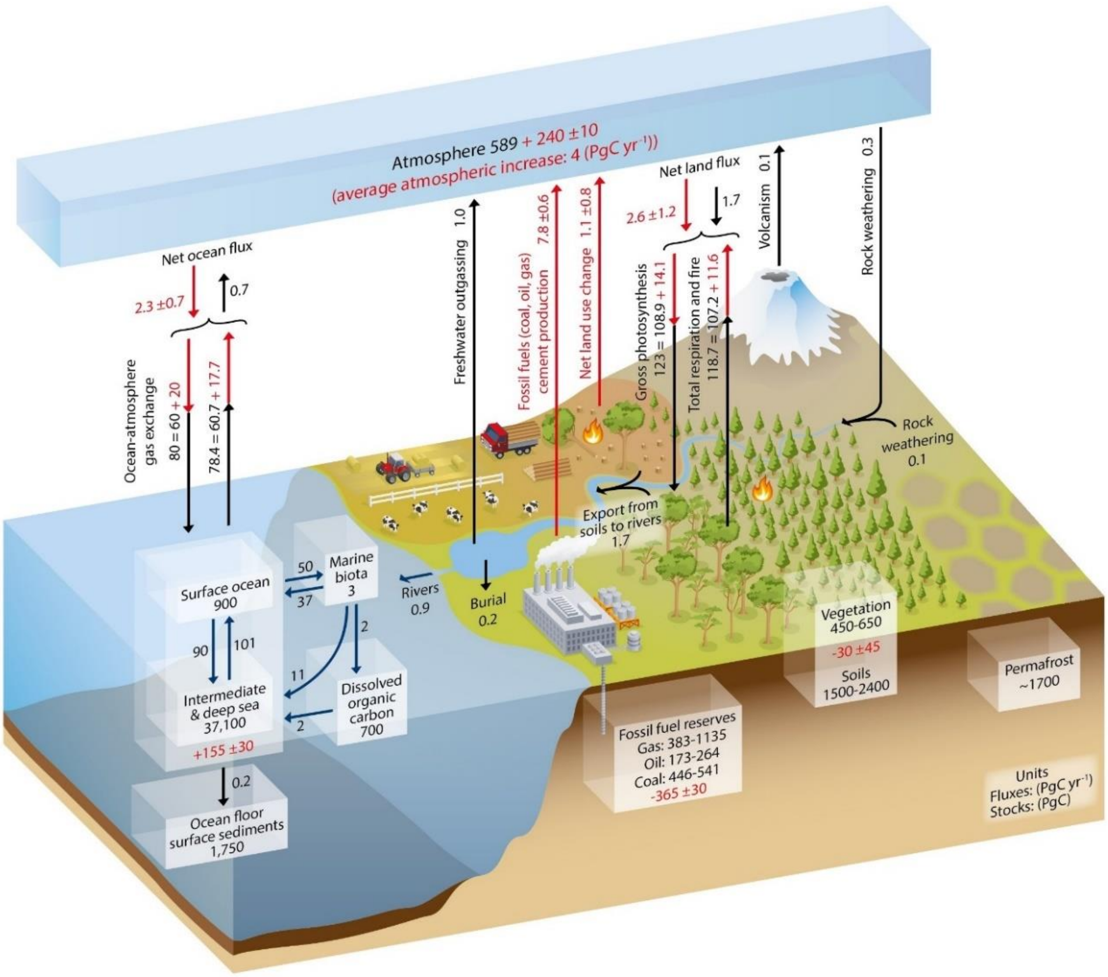


Figure 6-1: Simplified schematic of the global carbon cycle (IPCC, 2013)

The carbonate pump

Shell-producing marine organisms such as coccolithophores (a kind of phytoplankton) and other organisms such as bivalves are the primary drivers of this mechanism. They form their shells by precipitating calcium carbonate ($CaCO_3$) from bicarbonate and calcium ions into an organic matrix. Upon their death, the carbonates sink to the sea floor and either redissolve back into their respective ions, or form sedimentary rocks and enter the long-term carbon cycle.

Carbonate chemistry in seawater is complex and involves buffer solutions with interdependent variables, but the commonly used equilibrium below shows the formation of one molecule of calcium carbonate:

$$Ca^{2+} + 2HCO_3^- \rightleftharpoons CaCO_3 + CO_2 + H_2O$$

The equilibrium shows the calcium ion (2^+) needs two bicarbonate ions (1^-) to balance, forming a CO_3 ion (2^-). The carbon atom from the second bicarbonate ion is balanced out with a release of aqueous CO_2. From Henry's Law, this readjusts the equilibria of the different carbon species and the aqueous CO_2 is modelled as released into the atmosphere.

This can be shown another way: Total Alkalinity (TA) and Dissolved Inorganic Carbon (DIC) are used as 'master variables' to assess the impacts of CO_2 balances on the marine environment (Middelburg, 2019). As stated in the background section, DIC is the sum of the concentrations of aqueous CO_2 species in a solution and TA quantifies the ability of a solution to store DIC in equilibrium with a given pCO_2.

Figure 6-2, adapted from Middelburg (2019) shows the vector relationship between DIC and TA with CO_2 fluxes across the atmospheric/oceanic boundary, and the formation/dissolution of $CaCO_3$. It illustrates that the precipitation of $CaCO_3$ decreases both DIC and TA, leading to an efflux of CO_2. The slope of this graph is 1:2, which aligns with the work of Wolf-Gladrow, Zeebe, Klaas, Körtzinger, & Dickson (2007) and Gattuso, Pichon, & Frankignoulle (1995) who state that the formation of 1 mole of $CaCO_3$ always leads to a decrease of 1 mole in DIC and 2 moles TA in a closed system, even if a particular reaction is driven directly from CO_3^{2-} rather than HCO_3^-. This is because of the general oceanic equilibria, where taking one mole of CO_3^{2-} will just cause more HCO_3^- to form instead.

Furthermore, the graph also shows that this CO_2 efflux does not impact TA directly (it has a gradient of 0), but does have an effect on DIC in the open seawater system. Wolf-Gladrow et al. (2007) show that this is a key differentiator between a closed and open system. In an open system such as in the upper mixed layer of the ocean, the CO_2 outgassing further decreases DIC, driving the system forward. This can be seen in Figure 6-3.

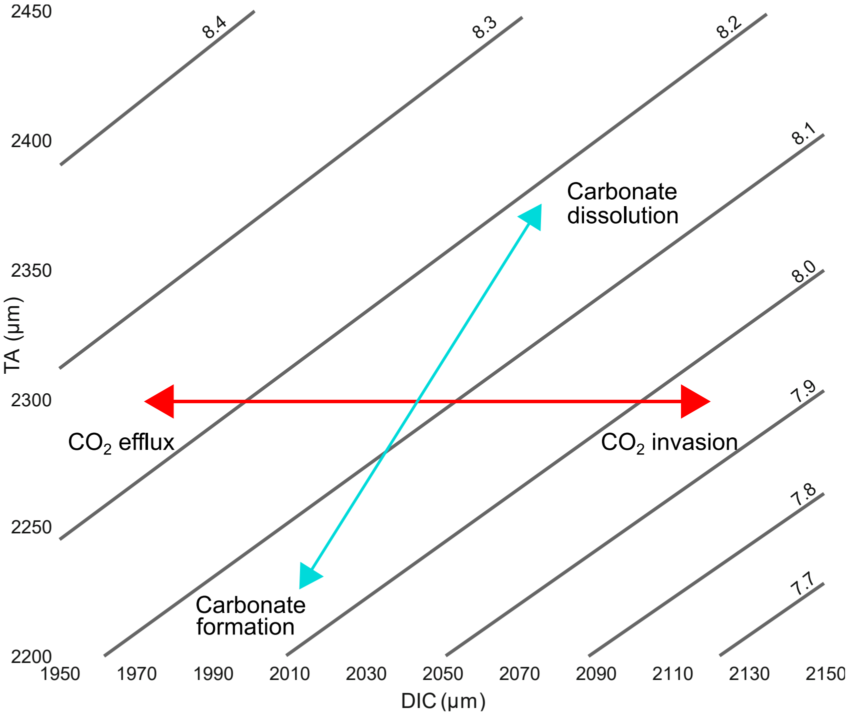


Figure 6-2: Vector diagram on TA-DIC plot showing pH changes due to CO_2 invasion and effluxes and carbonate dissolution and formation (precipitation). Adapted from Middelburg (2019)

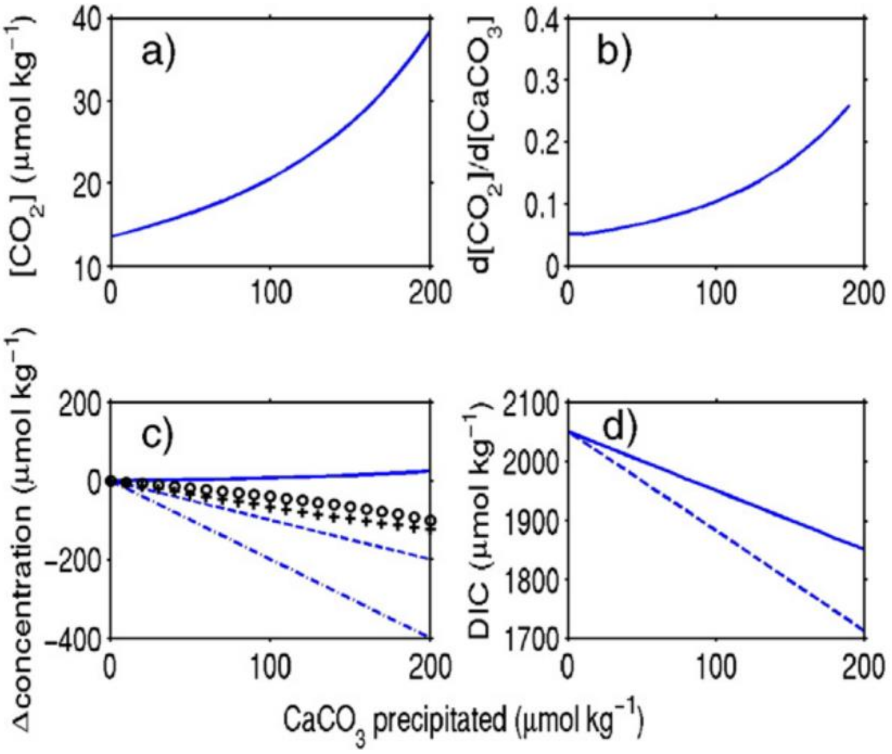


Figure 6-3: Changes of the carbonate system due to precipitation of $CaCO_3$ (Wolf-Gladrow, et al., 2007).

a) Closed system, CO_2 increases with $CaCO_3$ precipitation. b) Closed system: the change of CO_2 per mole of $CaCO_3$ precipitated (analogous to ψ) increases with decreasing concentration of carbonate. c) Closed system: changes in CO_2 [solid line], DIC [dashed line], TA [dash-dotted line], HCO_3^- (o's) and CO_3^{2-} (+'s). d) DIC decreases with $CaCO_3$ precipitation in the closed system, and this decrease is more significant in a closed system (dashed line).

Seawater buffering

The equilibrium reaction discussed above indicates that for every mole of $CaCO_3$ precipitated, one mole of CO_2 is released. This is mostly the case in freshwater, but the interactions of carbonate chemistry and chemical buffers in seawater reduce the amount of CO_2 liberated. Ware et al. (1992) modelled the aqueous CO_2 system with 8 interlinked equations and 10 variables and shows the relationship of released CO_2 to precipitated carbonate, *psi* (given the symbol ψ), as approximately 0.6. Specific calculations for this ratio are available using the *psi* function in the *seacarb* library for the statistical modelling package R, developed by Gattuso and Lavigne in 2008 (latest version from Gattuso, Epitalon, Lavigne, & Orr (2020)). This study uses this tool to develop a value of ψ for the New Zealand coastal waters where mussels and oysters are grown using pCO_2 and pH values.

Put simply, this buffering occurs because as the calcium carbonate is precipitated, the water becomes more acidic due to the removal of bicarbonate ions, lowering the pH slightly. The reduction in pH also lowers the solubility of CO_2 in the water, increasing the partial pressure of CO_2 (pCO_2) and triggering a release of CO_2 in an open system. This then increases pH and decreases pCO_2, but not to the same level that it was before, buffering the system (Ware, et al., 1992; Frankignoulle, et al., 1994; Middelburg, 2019). These are consistent with the vector diagram shown in Figure 6-2.

Carbon impacts & modelling implications

No single mole of CO_2 released from calcification can be tracked directly to the atmosphere, due to short term carbon biodynamics in the oceanic ecosystem and the fact that the ocean is a net carbon sink. Ware, Smith, & Reaka-Kudla (1992) reframe the process instead as a reduction in the CO_2 absorption potential of the ocean over a period of decades. Ray et al. (2018) suggest using this reduction potential as a direct GWP impact for LCA modelling.

These impacts are not confined to short term fluxes, however. Frankignoulle, Canon, & Gattuso, (1994) and Gattuso, Frankignoulle, & Wollast (1998) illustrate that in the geological medium term, carbonate precipitation can have significant changes in the carbon cycle. They show that reef generation and its associated carbonate precipitation is one of the primary driving factors of the increase in atmospheric carbon dioxide in the previous glacial-interglacial period.

Shell CO_2 Modelling Process

Ray et al. (2018) show that the following equation is used to calculate the mass of CO_2 released from a given shell mass. Three variables are needed; the mass of dry shell, the percentage calcium carbonate of the shell mass, and the ratio of CO_2 released to $CaCO_3$ precipitated (psi, ψ). The conversion factor between $CaCO_3$ and CO_2 is calculated as the ratio of molar masses. Bivalve shell is 95.7% $CaCO_3$ (Hamester, et al., 2012).

$$CO_2\ Release_{Shell\ Formation} = Shell\ Mass \times \psi \times \%\ Shell\ CaCO_3 \times \frac{44.01\frac{g}{mol}\ CO_2}{100.0869\frac{g}{mol}\ CaCO_3}$$

To calculate ψ, the *seacarb* library for the statistical analysis programme R is used (Gattuso, et al., 2020). The *psi* function takes a selection of arguments as inputs and returns the value for the given conditions. One option for this is to compute with the partial pressure of CO_2 (pCO_2) and pH as variables.

There is a linear relationship between PPM (moles CO_2 per million moles of air) and the pCO_2 ratio. However, this ratio is only valid in dry air so this was calculated directly, again using *seacarb*. The function *x2ppCO2* takes the arguments of salinity, water temperature, atmospheric pressure at sea level and atmospheric CO_2 (in ppm) to calculate pCO_2.

Average annual temperatures across coastal NZ waters are 15°C, and salinity is 34 PSU (Broekhuizen, 2015). Atmospheric CO_2 concentrations are 408ppm (NIWA, 2020). The code returned a figure of 401.2564 µatm pCO_2.

```
x2pCO2(S=34, T=15, Patm=1.0, xCO2=408)
```

With this figure for pCO_2 and the pH figure of 8.1 (Broekhuizen, 2015), ψ can be calculated:

```
psi(flag=21, var1=401.2564, var2=8.1, S=34, T=15, P=0, Pt=0,
Sit=0, pHscale="T", kf="x", k1k2="l", ks="d")
```

Other than the pH, pCO2, salinity and water temperature, all other variables were left as default, returning a final figure for psi of 0.694492. This is within the range of variables given by Ray et al. (2018).

Putting this figure into the final equation, we get a result of 0.292 kg CO_2 released per kg of bivalve shell. This is consistent with Morris & Humphrey (2018), which found a release of approximately 0.29 kg CO_2 released per kg of bivalve shell from mussel farms in Southern Portugal and ~0.39 kg CO_2 / kg of bivalve shell from an equivalent farm in the Baltic ocean. As mussels

Calculation of shell CO_2 released per kilogram of edible meat

Shellfish	Edible meat (kg)	Meat mass as a % of live weight	Shell mass (kg)	Shell CO_2 released (kg)
Pacific Oyster	1.00	20.8%	3.81	1.11
Greenshell Mussel	1.00	48.7%	1.05	0.31

Annex D Mitigation of Shell Formation Carbon Footprint

Mitigation potential

Given the equilibrium that drives the release of CO_2 is reversible, it asks the question: can shell waste be returned to the sea and dissolved so that aqueous CO_2 can be absorbed? This is a complex issue that is highly dependent on oceanic chemistry.

Figure 6-4 from Middelburg (2019) shows a diagram of how calcium carbonate dissolves in an oceanic environment. Surface oceans around the world are supersaturated with bicarbonate and carbonate ions and will therefore not readily dissolve shells. Net carbonate sediments remain on the seabed in the form of “snow” and can eventually become sedimentary rock such as limestone. In deeper water however, the higher pressure and lower temperature mean that solubility increases, and the water can become undersaturated.

Above the saturation horizon, very little $CaCO_3$ dissolves as surface waters are supersaturated. Below this horizon, water is at a higher pressure and has higher dissolved CO_2 from the decay of organic matter, meaning $CaCO_3$ will start to dissolve. Below the carbonate compensation depth, the rate of dissolution and matter influx match, resulting in sediment with very little $CaCO_3$ content. The snowline is very similar to this depth, with ‘snow’ being carbonate rich sediments.

Below the carbonate compensation depth, the rate of undersaturation is such that any carbonate export is dissolved at a rate greater than the influx, and therefore only open ocean deeper than this is viable for shell dumping and dissolution that does not result in shells sitting on the seabed.

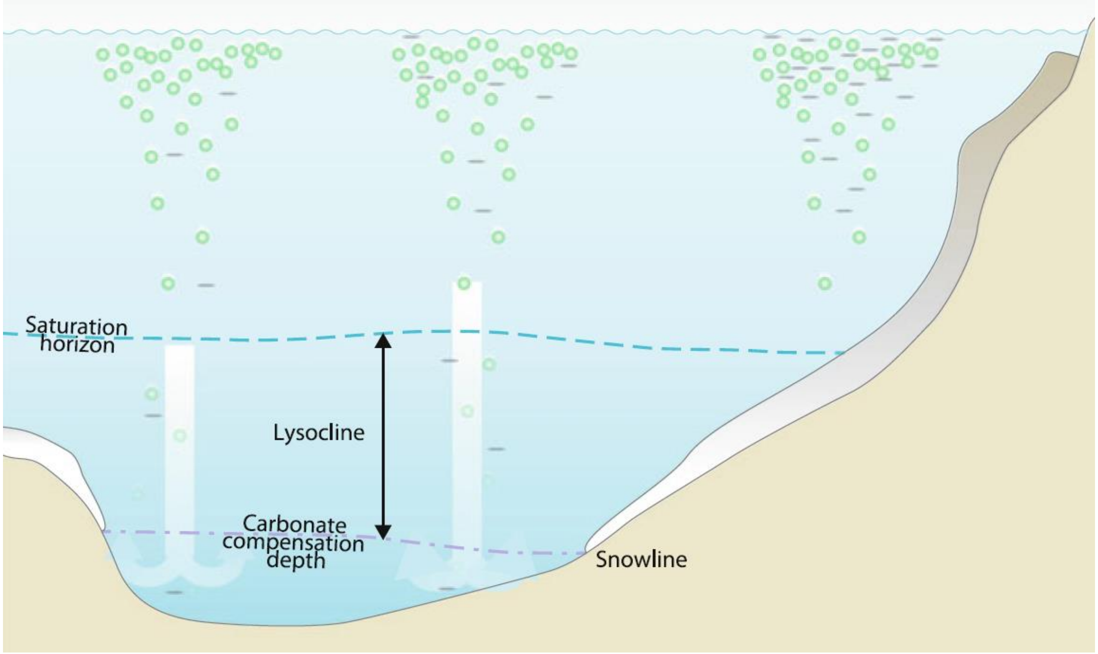


Figure 6-4: Carbonate compensation (Middelburg, 2019)

Given biological processes and differences in oceanic chemistry, this depth is not constant around the world. Figure 6-5 from Sulpis et al. (2018) shows this depth, and it is notable that coastal waters around New Zealand are all shallower than this and therefore not suitable for total and rapid dissolution. Part of the Tasman Sea off the coast of Fiordland is below this depth, but given the distance from processing facilities, and the associated financial costs and environmental impacts from transporting the waste shell to the dump site, it does not appear to be a viable option in the open ocean.

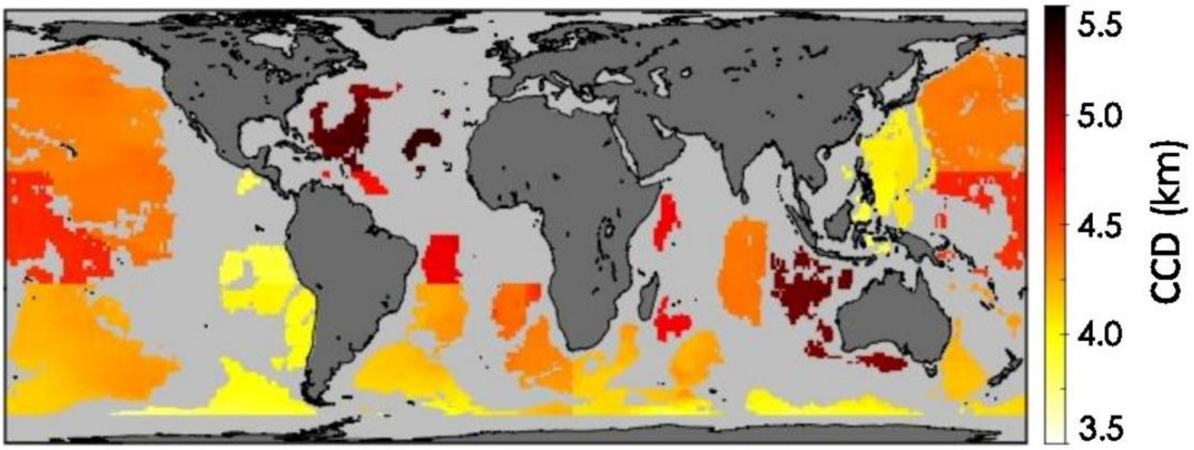


Figure 6-5: Global carbonate compensation depth, where grey indicates the depth is greater than that of the sea floor. From (Sulpis, et al., 2018)

There is one notable exception to this for the New Zealand shellfish industry. Law et al. (2020) conducted a study on the effects of using waste shell as a mitigation strategy against coastal oceanic acidification. The authors show that the Firth of Thames has a significantly lower pH than either the national average pH or sites in the Marlborough Sounds, and that coastal ecosystems are acidifying faster than oceanic ecosystems. Current Firth pH levels are estimated to be the same as the worst-case pH levels for NZ waters around 2100. Given the semi-enclosed nature of the Firth of Thames and the high level of acidic agricultural runoff from the Waihou River, the Firth is especially prone to these issues. Measurements show the carbonate saturation state fell below 1 at times, meaning that growing mussels began to dissolve faster than they grew.

The study was aimed at determining the effectiveness of buffering this acidification with waste shell dissolution, but did not explicitly measure rates of dissolution as a primary output. Indicative results show that at Sanford's EcoFarm in the Marlborough Sounds, 0.012% of shell mass suspended in bags along dropper lines dissolved per day over a three-week period. In contrast, experimental results from Abdulghani (2014) in Washington State indicate that in a corrosive coastal sediment environment (such as the Firth of Thames), mass is lost at 0.05% per day, or 27% of the total mass over a standard mussel grow cycle (18 months). Law et al. did not conclude that shell waste, either arranged along dropper ropes or deposited on the seabed was an effective solution for buffering ocean acidification. This was due to tidal flows carrying the alkalinity away from the farms, and the impracticality of integrating waste shell into the dropper lines.

However, if the data in these early-stage studies is accurate, there is significant potential for use in CO_2 mitigation. Taking the 0.012% mass loss per day figure from the Sanford farm in the Marlborough Sounds, it would take 22.8 years to completely dissolve a mass of shells. If the rates are closer to those identified by Abdulghani, it could take a mere 5.5 years to dissolve. Further study on dissolution rates in New Zealand coastal waters is needed to quantify the potential for mitigation, especially considering the large total masses of shell waste involved in the industry, and whether benthic habitats can support the influx of material. If these factors prove the option viable, the CO_2 released in the process of creating shells can essentially be re-sequestered, lowering the carbon footprint of the products.

Annex E Interactions with the Nitrogen Cycle

The nitrogen cycle within oceans is complex and is dependent on many variables. Processes included within the cycle are nitrogen fixation, assimilation, nitrification, anammox and denitrification (Voss, et al., 2013). These processes are not entirely understood and are dependent on local conditions, so a full analysis of their effects is beyond the scope of this study. In order to understand the potential impacts that bivalve (a term encompassing both mussel and oyster) farming has on the oceans and the atmosphere, this study has considered the effects of nitrogen fixation by mussels and oysters during filter feeding as well as the gases released during incomplete denitrification. A conservative approach has been taken to ensure that any benefits which are only applicable in limited circumstances are not included.

Nitrogen uptake as a eutrophication buffer

Bivalves feed by filtering particles, like phytoplankton, other microorganisms and detritus suspended in the sea water around them. This contributes to the removal of nitrogen sources, which becomes either shellfish tissue, or is excreted as urine and faeces (Peterson, et al., 2018).

Mussel aquaculture removes a proportion of the nitrogen loading from rivers, acting somewhat as a eutrophication buffer. Table 6-2, taken from Knight (2013) provides data which suggests that such nitrogen removal in the Sounds is small in comparison to the natural oceanic exchange, but not to other sources such as river input and other aquaculture.

Table 6-2 Nitrogen flux in and out of Pelorus and Queen Charlotte Sound (Knight, 2013)

Source	Pelorus Sound (tonnes N)	Queen Charlotte Sound (tonnes N)
Ocean exchange	1050-2100	412-825
River input	580	16.6
Picton wastewater	-	9
Existing salmon	504	812
Mussel farms	-266	-11.8
Denitrification	-465	-367

It is also worth noting that in nitrogen-poor systems, it may not be reasonable to suggest that there is any beneficial nitrogen uptake from shellfish farming. Seasonal and interannual weather can change the rate of change and the system response to nitrogen flux. During summer, nitrogen influx into a sound may decrease due to lower river levels. Warmer water increases the growth rate, and consequently the uptake, in phytoplankton in response to dissolved nitrogen in the water.

For the purposes of this study, there is no nitrogen removal from sea water modelled. This is to be conservative, as well as the fact the methodology used (Heijungs, et al., 1992) does not include characterisation factors for the removal of nutrients from water.

Denitrification

Denitrification is a term for the series of reactions where nitrates and nitrites are reduced to gaseous forms of nitrogen (Skiba, 2008). This process can contribute significantly to global warming potential environmental impacts, particularly when nitrates are not fully converted to nitrogen, only into nitrous oxide (N_2O) in the first step.

Bivalves release a small amount of nitrous oxide, as well as a small amount of methane, which contribute nontrivially to the global warming impact of the mussel's life cycle. This release is increased with higher fixed nitrogen levels or a hypoxic or acidic environment (Garate, et al., 2019). Sources for the nitrous oxide production in bivalves are poorly understood, although Stief et al. (2009) suggests that it comes from bivalve's digestive tracts, while Gárate et. al. (2019) finds that it appears to be a mixture of this and the microbial biofilm on the exterior of the bivalve shell. Using nitrous oxide and methane production rates from Bonaglia et al. (2017) and assuming an 18-month average life cycle for mussels, the amount of methane and nitrous oxide released per kg of bivalves has been calculated below. It should be noted that Bonaglia et al. (2017) studied a different species living wild (not cultured) in the Baltic Sea and that these estimations therefore are connected to large uncertainty.

The impact of denitrification will depend on the localized conditions of the body of water. The local oxygen levels will influence the rate of denitrification occurring in that area. According to water quality reports prepared by the National Institute of Water and Atmospheric Research Ltd (NIWA, 2018), oxygen levels seldom fall below 90% in the Marlborough Sounds. By contrast, oxygen levels in the Northern Firth of Thames can fall to around 60% in warmer months (NIWA, Firth of Thames Water Quality and Ecosystem Health, 2015). From a global warming perspective, it has been assumed that all methane and nitrous oxide produced by bivalves will reach the atmosphere without further reaction, in order to understand the full potential impact.

From Bonaglia et al. (2017)*:*

Rate of CH_4 production from bivalves (Limecola balthica) in an incubated bottle:

$$R_{CH_4} = 3.0\ \mathrm{nmol}\ (\mathrm{g\ wet\ weight})^{-1}\ h^{-1}$$

Rate of N_2O production from bivalves (Limecola balthica) in an incubated bottle:

$$R_{N_2O} = 0.5\ \mathrm{nmol}\ (\mathrm{g\ wet\ weight})^{-1}\ h^{-1}$$

Methane per kg bivalves:

$$m_{CH_4} = R_{CH4} * \frac{mol}{nmol} * \frac{hours}{life\ cycle} * M_{CH_4} * \frac{g}{kg}$$

$$m_{CH_4} = 3\ nmol * g^{-1} bivalves * hour^{-1} * \frac{1\ mol}{10^9 nmol} * \frac{13140\ hours}{life\ cycle} * \frac{16.04\ g}{mol} * \frac{1000\ g\ bivalves}{1\ kg\ bivalves}$$

$$m_{CH_4} = 0.632\ g\ CH_4\ kg^{-1} bivalves\ farmed\ (used\ for\ oysters)$$

Adjusting for 9% of mussels that are blue mussels, and are thrown overboard:

$$m_{CH_4} = 1.09 * 0.632\ g\ CH_4\ kg^{-1} bivalves = \ 0.689\ g\ CH_4\ kg^{-1} green\ mussels\ farmed$$

Similarly, for nitrous oxide:

$$m_{N_2O} = R_{N_2O} * \frac{mol}{nmol} * \frac{hours}{life\ cycle} * M_{N_2O} * \frac{g}{kg}$$

$$m_{CH_4} = 0.5\,nmol * g^{-1} bivalves * hour^{-1} * \frac{1\,mol}{10^9 nmol} * \frac{13140\,hours}{life\ cycle} * \frac{44.01\,g}{mol} * \frac{1000\,g\,bivalves}{1\,kg\,bivalves}$$

$$m_{N_2O} = 0.289\,g\,N_2O\,kg^{-1} bivalves\,farmed\ (used\ for\ oysters)$$

Adjusting for the growth of blue mussels:

$$m_{CH_4} = 1.09 * 0.289\,g\,N_2O\,kg^{-1} bivalves = \ 0.315\,g\,N_2O\,kg^{-1} green\,mussels\,farmed$$

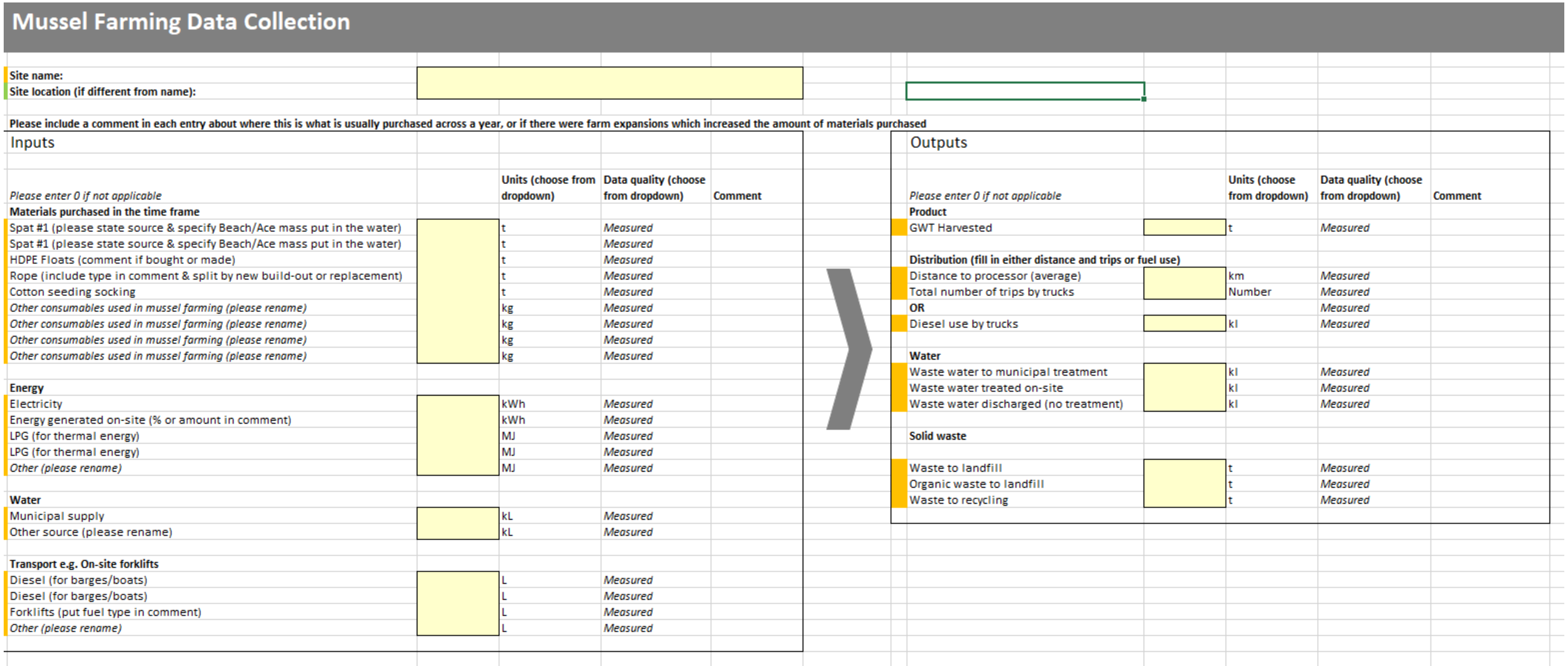
Calculation of shellfish CH_4 and N_2O released per kilogram of edible meat

Table 6-3: Shellfish CH_4 and N_2O release during shellfish growth

Shellfish	Unit	Pacific Oyster	Greenshell Mussel
Total shellfish mass, per kg of edible meat	kg	4.81	2.05
CH4 produced per kg shellfish	kg	6.32E-04	6.89E-04
N2O produced per kg shellfish	kg	2.89E-04	3.15E-04
CH4 produced per kg meat	kg	3.04E-03	1.41E-03
N2O produced per kg meat	kg	1.39E-03	6.46E-04
GWP from CH4 per kg meat	kg CO_2e	9.12E-02	4.24E-02
GWP from N2O per kg meat	kg CO_2e	3.68E-01	1.71E-01
Total GWP per kg meat	kg CO_2e	4.60E-01	2.13E-01

Annex F Data Collection Sheets

Figure 6-6 to Figure 6-10 show the data collection templates used to drive the information collection of this study.



Mussel Farming Data Collection

Site name:

Site location (if different from name):

Please include a comment in each entry about where this is what is usually purchased across a year, or if there were farm expansions which increased the amount of materials purchased

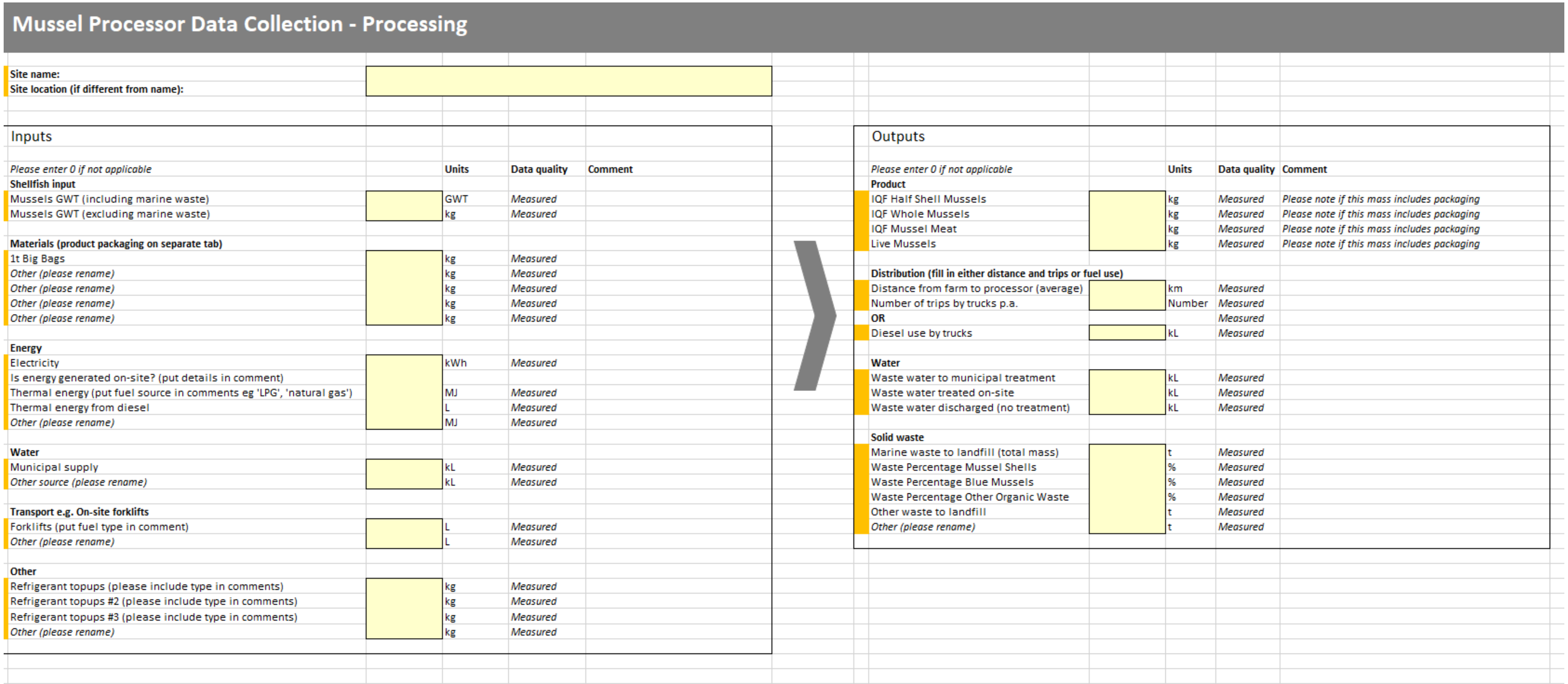
Inputs

Please enter 0 if not applicable		**Units (choose from dropdown)**	**Data quality (choose from dropdown)**	**Comment**
Materials purchased in the time frame				
Spat #1 (please state source & specify Beach/Ace mass put in the water)		t	*Measured*	
Spat #1 (please state source & specify Beach/Ace mass put in the water)		t	*Measured*	
HDPE Floats (comment if bought or made)		t	*Measured*	
Rope (include type in comment & split by new build-out or replacement)		t	*Measured*	
Cotton seeding socking		t	*Measured*	
Other consumables used in mussel farming (please rename)		kg	*Measured*	
Other consumables used in mussel farming (please rename)		kg	*Measured*	
Other consumables used in mussel farming (please rename)		kg	*Measured*	
Other consumables used in mussel farming (please rename)		kg	*Measured*	
Energy				
Electricity		kWh	*Measured*	
Energy generated on-site (% or amount in comment)		kWh	*Measured*	
LPG (for thermal energy)		MJ	*Measured*	
LPG (for thermal energy)		MJ	*Measured*	
Other (please rename)		MJ	*Measured*	
Water				
Municipal supply		kL	*Measured*	
Other source (please rename)		kL	*Measured*	
Transport e.g. On-site forklifts				
Diesel (for barges/boats)		L	*Measured*	
Diesel (for barges/boats)		L	*Measured*	
Forklifts (put fuel type in comment)		L	*Measured*	
Other (please rename)		L	*Measured*	

Outputs

Please enter 0 if not applicable		**Units (choose from dropdown)**	**Data quality (choose from dropdown)**	**Comment**
Product				
GWT Harvested		t	*Measured*	
Distribution (fill in either distance and trips or fuel use)				
Distance to processor (average)		km	*Measured*	
Total number of trips by trucks		Number	*Measured*	
OR			*Measured*	
Diesel use by trucks		kl	*Measured*	
Water				
Waste water to municipal treatment		kl	*Measured*	
Waste water treated on-site		kl	*Measured*	
Waste water discharged (no treatment)		kl	*Measured*	
Solid waste				
Waste to landfill		t	*Measured*	
Organic waste to landfill		t	*Measured*	
Waste to recycling		t	*Measured*	

Figure 6-6: Data collection sheet used for mussel farms



Mussel Processor Data Collection - Processing

Site name:
Site location (if different from name):

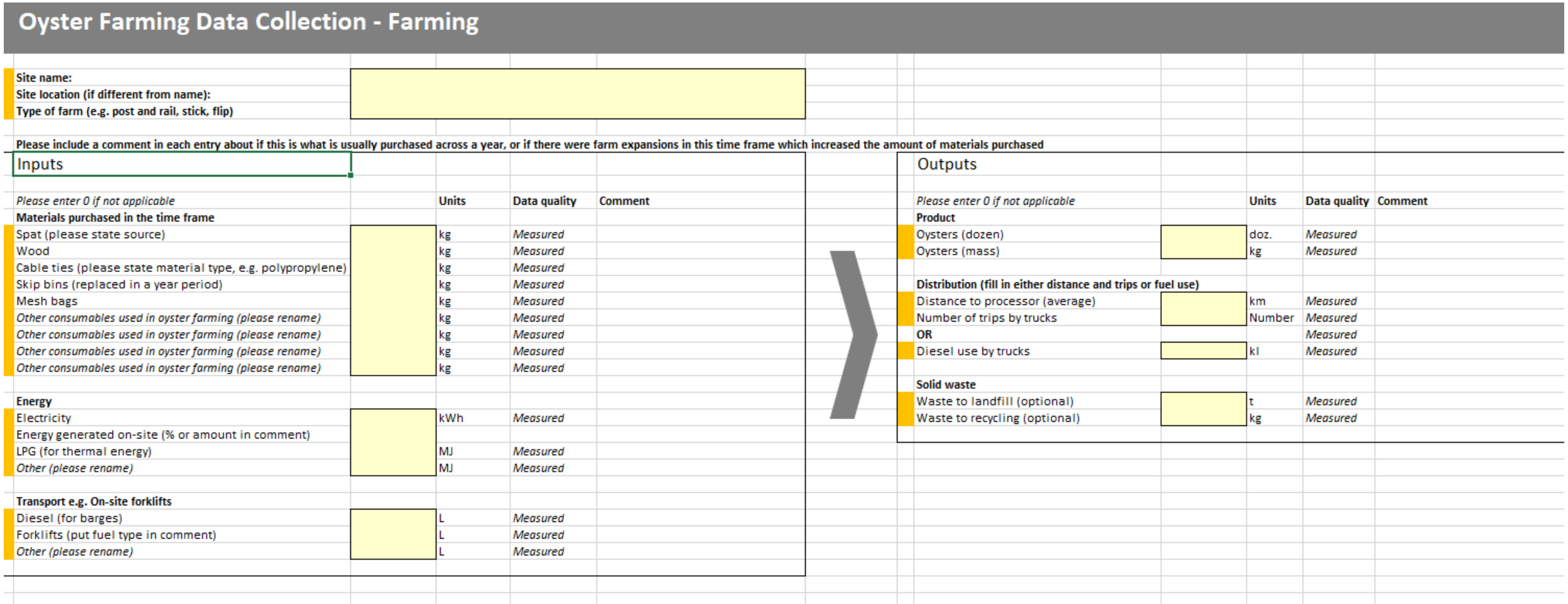
Inputs

Please enter 0 if not applicable		**Units**	**Data quality**	**Comment**
Shellfish input				
Mussels GWT (including marine waste)		GWT	*Measured*	
Mussels GWT (excluding marine waste)		kg	*Measured*	
Materials (product packaging on separate tab)				
1t Big Bags		kg	*Measured*	
Other (please rename)		kg	*Measured*	
Other (please rename)		kg	*Measured*	
Other (please rename)		kg	*Measured*	
Other (please rename)		kg	*Measured*	
Energy				
Electricity		kWh	*Measured*	
Is energy generated on-site? (put details in comment)				
Thermal energy (put fuel source in comments eg 'LPG', 'natural gas')		MJ	*Measured*	
Thermal energy from diesel		L	*Measured*	
Other (please rename)		MJ	*Measured*	
Water				
Municipal supply		kL	*Measured*	
Other source (please rename)		kL	*Measured*	
Transport e.g. On-site forklifts				
Forklifts (put fuel type in comment)		L	*Measured*	
Other (please rename)		L	*Measured*	
Other				
Refrigerant topups (please include type in comments)		kg	*Measured*	
Refrigerant topups #2 (please include type in comments)		kg	*Measured*	
Refrigerant topups #3 (please include type in comments)		kg	*Measured*	
Other (please rename)		kg	*Measured*	

Outputs

Please enter 0 if not applicable		**Units**	**Data quality**	**Comment**
Product				
IQF Half Shell Mussels		kg	*Measured*	*Please note if this mass includes packaging*
IQF Whole Mussels		kg	*Measured*	*Please note if this mass includes packaging*
IQF Mussel Meat		kg	*Measured*	*Please note if this mass includes packaging*
Live Mussels		kg	*Measured*	*Please note if this mass includes packaging*
Distribution (fill in either distance and trips or fuel use)				
Distance from farm to processor (average)		km	*Measured*	
Number of trips by trucks p.a.		Number	*Measured*	
OR			*Measured*	
Diesel use by trucks		kL	*Measured*	
Water				
Waste water to municipal treatment		kL	*Measured*	
Waste water treated on-site		kL	*Measured*	
Waste water discharged (no treatment)		kL	*Measured*	
Solid waste				
Marine waste to landfill (total mass)		t	*Measured*	
Waste Percentage Mussel Shells		%	*Measured*	
Waste Percentage Blue Mussels		%	*Measured*	
Waste Percentage Other Organic Waste		%	*Measured*	
Other waste to landfill		t	*Measured*	
Other (please rename)		t	*Measured*	

Figure 6-7: Data collection sheet used for mussel processors



Oyster Farming Data Collection - Farming

Site name:
Site location (if different from name):
Type of farm (e.g. post and rail, stick, flip)

Please include a comment in each entry about if this is what is usually purchased across a year, or if there were farm expansions in this time frame which increased the amount of materials purchased

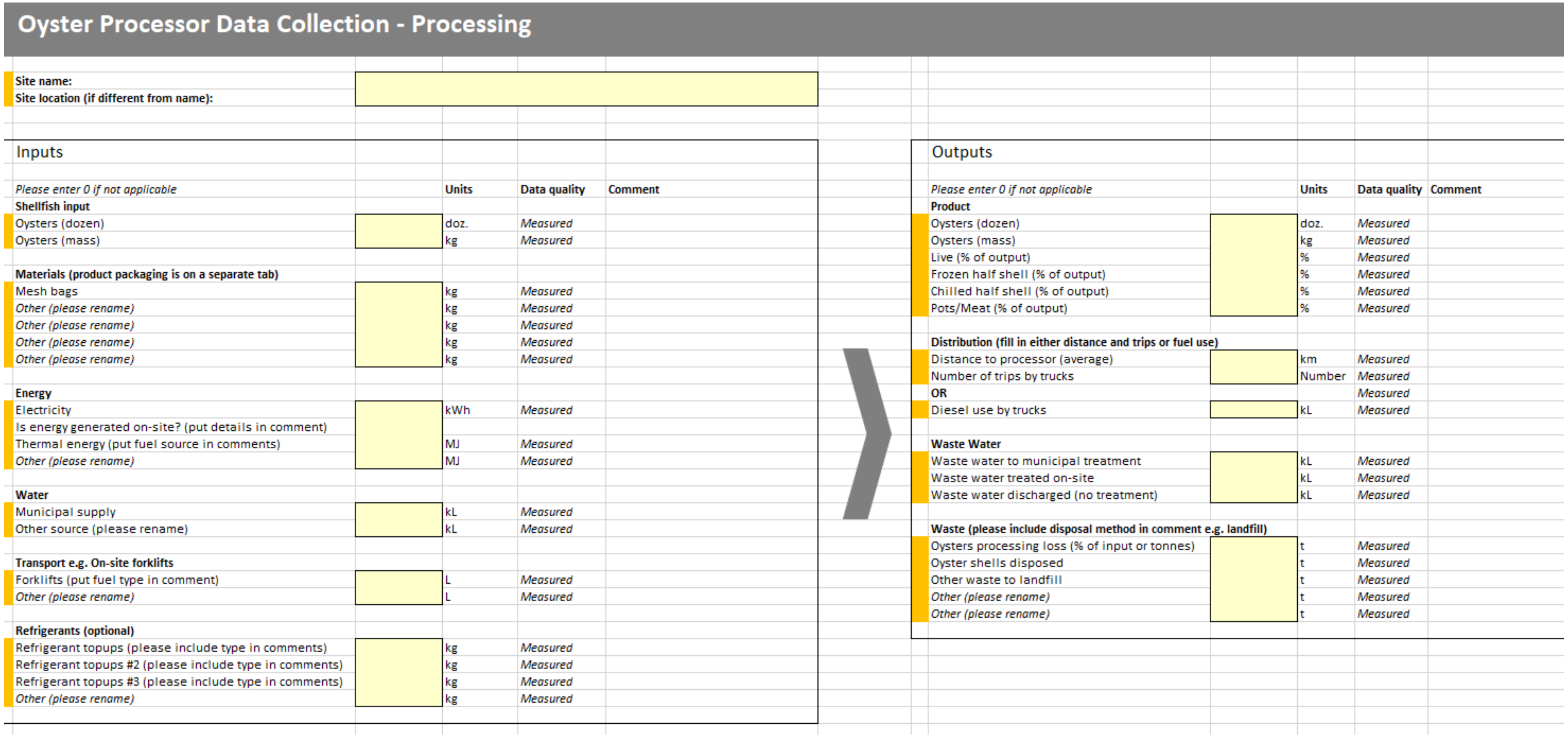
Inputs

Please enter 0 if not applicable		**Units**	**Data quality**	**Comment**
Materials purchased in the time frame				
Spat (please state source)		kg	*Measured*	
Wood		kg	*Measured*	
Cable ties (please state material type, e.g. polypropylene)		kg	*Measured*	
Skip bins (replaced in a year period)		kg	*Measured*	
Mesh bags		kg	*Measured*	
Other consumables used in oyster farming (please rename)		kg	*Measured*	
Other consumables used in oyster farming (please rename)		kg	*Measured*	
Other consumables used in oyster farming (please rename)		kg	*Measured*	
Other consumables used in oyster farming (please rename)		kg	*Measured*	
Energy				
Electricity		kWh	*Measured*	
Energy generated on-site (% or amount in comment)				
LPG (for thermal energy)		MJ	*Measured*	
Other (please rename)		MJ	*Measured*	
Transport e.g. On-site forklifts				
Diesel (for barges)		L	*Measured*	
Forklifts (put fuel type in comment)		L	*Measured*	
Other (please rename)		L	*Measured*	

Outputs

Please enter 0 if not applicable		**Units**	**Data quality**	**Comment**
Product				
Oysters (dozen)		doz.	*Measured*	
Oysters (mass)		kg	*Measured*	
Distribution (fill in either distance and trips or fuel use)				
Distance to processor (average)		km	*Measured*	
Number of trips by trucks		Number	*Measured*	
OR			*Measured*	
Diesel use by trucks		kl	*Measured*	
Solid waste				
Waste to landfill (optional)		t	*Measured*	
Waste to recycling (optional)		kg	*Measured*	

Figure 6-8: Data collection sheet used for oyster farms



Oyster Processor Data Collection - Processing

Site name:
Site location (if different from name):

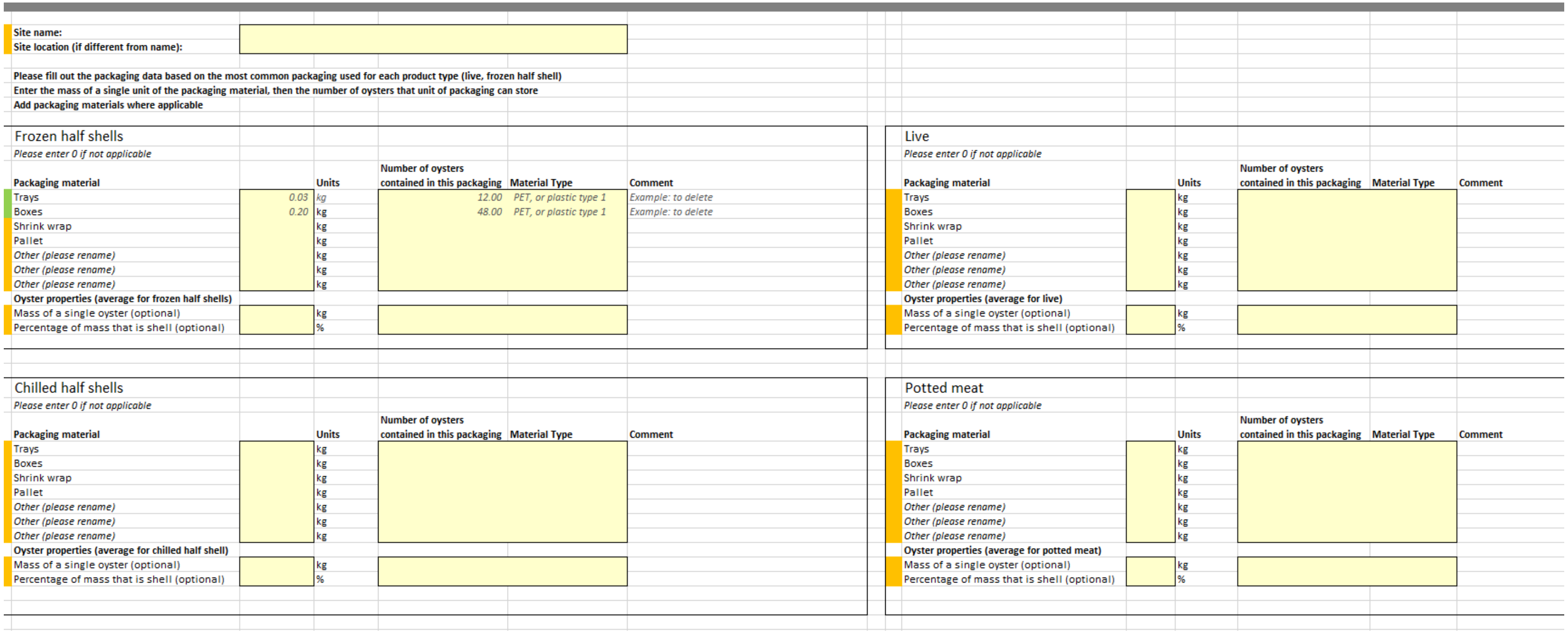
Inputs

	Units	Data quality	Comment
Please enter 0 if not applicable	**Units**	**Data quality**	**Comment**
Shellfish input			
Oysters (dozen)	doz.	*Measured*	
Oysters (mass)	kg	*Measured*	
Materials (product packaging is on a separate tab)			
Mesh bags	kg	*Measured*	
Other (please rename)	kg	*Measured*	
Other (please rename)	kg	*Measured*	
Other (please rename)	kg	*Measured*	
Other (please rename)	kg	*Measured*	
Energy			
Electricity	kWh	*Measured*	
Is energy generated on-site? (put details in comment)			
Thermal energy (put fuel source in comments)	MJ	*Measured*	
Other (please rename)	MJ	*Measured*	
Water			
Municipal supply	kL	*Measured*	
Other source (please rename)	kL	*Measured*	
Transport e.g. On-site forklifts			
Forklifts (put fuel type in comment)	L	*Measured*	
Other (please rename)	L	*Measured*	
Refrigerants (optional)			
Refrigerant topups (please include type in comments)	kg	*Measured*	
Refrigerant topups #2 (please include type in comments)	kg	*Measured*	
Refrigerant topups #3 (please include type in comments)	kg	*Measured*	
Other (please rename)	kg	*Measured*	

Outputs

	Units	Data quality	Comment
Please enter 0 if not applicable	**Units**	**Data quality**	**Comment**
Product			
Oysters (dozen)	doz.	*Measured*	
Oysters (mass)	kg	*Measured*	
Live (% of output)	%	*Measured*	
Frozen half shell (% of output)	%	*Measured*	
Chilled half shell (% of output)	%	*Measured*	
Pots/Meat (% of output)	%	*Measured*	
Distribution (fill in either distance and trips or fuel use)			
Distance to processor (average)	km	*Measured*	
Number of trips by trucks	Number	*Measured*	
OR		*Measured*	
Diesel use by trucks	kL	*Measured*	
Waste Water			
Waste water to municipal treatment	kL	*Measured*	
Waste water treated on-site	kL	*Measured*	
Waste water discharged (no treatment)	kL	*Measured*	
Waste (please include disposal method in comment e.g. landfill)			
Oysters processing loss (% of input or tonnes)	t	*Measured*	
Oyster shells disposed	t	*Measured*	
Other waste to landfill	t	*Measured*	
Other (please rename)	t	*Measured*	
Other (please rename)	t	*Measured*	

Figure 6-9: Data collection sheet used for mussel processors



Site name:
Site location (if different from name):

Please fill out the packaging data based on the most common packaging used for each product type (live, frozen half shell)
Enter the mass of a single unit of the packaging material, then the number of oysters that unit of packaging can store
Add packaging materials where applicable

Frozen half shells

Please enter 0 if not applicable

Packaging material		**Units**	**Number of oysters contained in this packaging**	**Material Type**	**Comment**
Trays	*0.03*	*kg*	*12.00*	*PET, or plastic type 1*	*Example: to delete*
Boxes	*0.20*	kg	*48.00*	*PET, or plastic type 1*	*Example: to delete*
Shrink wrap		kg			
Pallet		kg			
Other (please rename)		kg			
Other (please rename)		kg			
Other (please rename)		kg			
Oyster properties (average for frozen half shells)					
Mass of a single oyster (optional)		kg			
Percentage of mass that is shell (optional)		%			

Live

Please enter 0 if not applicable

Packaging material		**Units**	**Number of oysters contained in this packaging**	**Material Type**	**Comment**
Trays		kg			
Boxes		kg			
Shrink wrap		kg			
Pallet		kg			
Other (please rename)		kg			
Other (please rename)		kg			
Other (please rename)		kg			
Oyster properties (average for live)					
Mass of a single oyster (optional)		kg			
Percentage of mass that is shell (optional)		%			

Chilled half shells

Please enter 0 if not applicable

Packaging material		**Units**	**Number of oysters contained in this packaging**	**Material Type**	**Comment**
Trays		kg			
Boxes		kg			
Shrink wrap		kg			
Pallet		kg			
Other (please rename)		kg			
Other (please rename)		kg			
Other (please rename)		kg			
Oyster properties (average for chilled half shell)					
Mass of a single oyster (optional)		kg			
Percentage of mass that is shell (optional)		%			

Potted meat

Please enter 0 if not applicable

Packaging material		**Units**	**Number of oysters contained in this packaging**	**Material Type**	**Comment**
Trays		kg			
Boxes		kg			
Shrink wrap		kg			
Pallet		kg			
Other (please rename)		kg			
Other (please rename)		kg			
Other (please rename)		kg			
Oyster properties (average for potted meat)					
Mass of a single oyster (optional)		kg			
Percentage of mass that is shell (optional)		%			

Figure 6-10: Shellfish product packaging

Annex G Confidential Data

This data is not part of the publication communication of this study, but was submitted to the review panel for their consideration.

Microsoft Excel files:

- Collated Mussel Data 2021-06-27 - Clean.xlsx
- Collated Oyster Data 2021-06-27 - Clean.xlsx

Annex H Critical Review Commentary